

Wave-Driven Longshore Currents in the Surf Zone

Hydrodynamic validation of Delft3D

Roald Treffers

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Deltares

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Abstract								
Recent study has shown that 3D computations of the morphological development of a coast shows irregularities compared with the 2DH (depth-averaged) computations. Therefore a validation of the surf zone currents computed using the 2DH (depth-averaged) and 3D approach in Delft3D is made. The 2DH and 3D approach are compared using an idealized case and validated using data from the laboratory experiment performed by Reniers and Battjes and data from SandyDuck97 field measurements. The 3D approach underestimates the wave-driven longshore current compared with the 2DH approach. The longshore current computations in the 3D approach are dependent on the thickness of the computational layer just above the bed. In the 3D approach the bed shear stress is computed using the quadratic friction law and the velocity in the computational layer just above the bed as input, and the assumption of a logarithmic distribution of the longshore current. The dependency is caused by the assumption of a logarithmic velocity distribution in the computation of the bed shear stress. Due to wave breaking enhanced turbulence this assumption is not valid. Computing the bed shear stress using the velocity in the computational layer just above the edge of the wave boundary layer solves the layer dependency. This new method of computing the bed shear stress in particular and the longshore current computations by Delft3D in general are extensively validated. The 2DH and 3D approach agree well with the measurements for both the laboratory and the field data. For the laboratory experiments the longshore currents are underestimated in the bar trough. The wave height is the bar trough is overestimated, which might causes the underestimation of the longshore current since too little wave energy is dissipated. It is recommended to further examine the translation of wave forces to a current. For the field experiments the longshore currents are generally overestimated near the coast. The wave height computation showed a reasonable agreement with the measurements but also a systematically overestimation. More attention should be paid into accurately modelling the wave height and the wave height decay. Also the vertical distribution of the current velocity is compared with data from the SandyDuck97 measurements and showed a reasonable agreement.								
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Preface

This thesis concludes my Master of Science at the faculty of Civil Engineering and Geosciences of Delft University of Technology. This Master thesis was carried out at Deltares and describes the modelling of wave-induced currents in the surf zone. The longshore flow of water is in particular important for morphological related topics. Efforts made using Delft3D to compute this flow of water are examined, improved and discussed.

I want to thank my graduation committee for their interest, enthusiasm and support. Jebbe van der Werf since I could always bother him with questions and discussions, which I really appreciated. Marcel Zijlema for his clarifying view, from the department of Environmental Fluid Mechanics of Delft University of Technology, on this research. I also want to thank prof. Marcel Stive for his involvement during my Master study. Without the support and enthusiasm of prof. Marcel Stive I would not have had the opportunity of performing my Master project in New Orleans, which eventually led to this Master thesis topic. Finally, I would like to thank Maarten van Ormondt and Dirk-Jan Walstra for making this Master thesis possible for me at Deltares. Without their enthusiasm for wave-driven currents I would not have been able to undertake this thesis.

I really enjoyed working at Deltares and want to thanks my fellow ‘colleagues’ at Deltares. I appreciated the generosity of everyone and their willingness of answering all kind of questions. Furthermore, without the fellow graduate students at Deltares my time would not be this interesting and therefore I would like to thank; Renske, John, Claire, Anna, Carola, Steven, Sepehr, Lars, Thijs, Arend, Wouter, Chris, Reynald and especially Marten. I enjoyed all the discussions, jokes, walks around the Deltares place, the lunches and of course the ever popular pancakes on Friday.

I want to thank my friends in Delft who supported me during my graduation thesis and reminded me that a drink now and then is absolutely necessary in order to complete this research with success. My house-mates I want to thank for all support, meal cooked while I was working till late and the vivid discussions on waves, currents and all other relevant topics. Finally and above all, I want to thank my family who have supported me from the beginning to the end of my study in Delft. For more than six years they have stood behind me and supported me in every choice I made. Without them the fantastic time in Delft would not have been possible.

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Summary

As waves approach a coastline under an oblique angle the waves first increase in height before eventually breaking. The area in front of the coast where wave-breaking occurs is called the surf zone. As waves break, wave energy is converted into a flow in alongshore and cross-shore direction. These currents are important for coastal morphology related topics. The process-based numerical modelling program Delft3D is capable of computing the wave-driven currents in the surf zone for morphological related problems. Recent study showed that the 3D approach in Delft3D shows irregularities compared with the 2DH (depth-averaged) approach. Using the 3D approach a vertical distribution of the flow velocity can be computed, which is important for wave-induced suspended sediment transport related problems.

This research focuses on wave-driven currents in the surf zone. The goal is (i) to determine what the main driving forces of the currents in the surf zone are and how these currents are computed for morphological related topics in Delft3D. (ii) To determine what the differences are between the 2DH and 3D computed longshore currents and, what the causes are of the 3D approach to deviate from the 2DH approach. Furthermore, (iii) to determine the performance of both the 2DH and 3D approach of computing the wave-driven longshore currents in the surf zone. The wave-induced currents are computed for an idealised case and validated for a laboratory experiment and a field experiment.

The radiation stress theory developed by Longuet-Higgins and Stewart describes the translation of wave forces to a flow of water based on the so-called radiation stresses, which are induced by waves. The cross-shore gradients in the longshore stresses need to be counteracted by a flow-induced bed shear stress. The radiation theory is complemented with the roller theory, which delays the transfer of wave energy to a flow by first converting the wave energy to a roller energy, which travels on top of the wave before dissipating into a flow. For stationary situations, Delft3D computes the longshore currents using the roller dissipation induced force. The 3D approach takes wave-induced production of turbulence, streaming and Stokes drift into account aiming at a realistic simulation of the vertical profile of the velocity. Furthermore, the bed shear stress is computed using the quadratic friction law with the velocity in the computational layer just above the bed as input. Furthermore, also the assumption is made of a vertical logarithmic distribution of the longshore current.

To compare the 2DH and 3D approach in Delft3D an idealised case is used. This concerns a straight and uniform coast under the influence of waves only. The currents computed using the 3D approach is compared with those computed using the 2DH approach. The longshore currents in the surf zone in the 3D approach are underestimated (up to a factor two for small angles of incident waves) independent on the chosen wave climate. However, more remarkable, the 3D approach is dependent on the chosen thickness of the computational layer just above the bed. The velocity in this computational layer is used in the quadratic friction law. Reducing the thickness of the computational layer, results in a further underestimation of the wave-driven longshore currents in the surf zone. In case the flow is driven by a gradient in the water level, then there is little dependency on the thickness of the computational layer just above the bed. This is due to the method used of computing the bed shear stress in the 3D approach in the present of waves. Wave-breaking induced enhancement of vertical mixing results in a more vertically uniform distribution of the longshore current and therefore the assumption of a logarithmic vertical distribution is no longer valid. This results in an overestimation of the flow-induced bed shear stress and therefore the flow velocity becomes lower if the thickness of the computational layer just above the bed decreases. The layer dependency can be overcome by using the velocity in a fixed point in the vertical, which is independent on the thickness of the bottom computational layer. Using the velocity in the computational layer above the edge of the wave-boundary layer solves the dependency on the thickness of the computational layer just above the bed.

The new method of computing the bed shear stress is validated using the laboratory experiments performed by Reniers and Battjes. The comparison is made for a case of random waves approaching a barred beach under an angle. The new method of computing the bed shear stress improves the accuracy of the 3D computations compared with measurements and after calibration; both the results from the 2DH and 3D approach correspond well with measurements. However, the longshore current in the bar trough is underestimated by both the 2DH and 3D approach. The wave height is overestimated in the bar trough, too little wave energy is dissipated. This might cause the observed deviation in the longshore current. Furthermore, an extensive model analysis is performed by varying parameters in Delft3D. Remarkable is that when the currents are computed based on the total radiation stress induced force (instead of the roller induced force) the results deviate significantly from the measurements. The cause for this is unclear and might be due to numerical (implementation) errors, but it is recommended to compute the currents in Delft3D based on the total radiation stress induced force, since this is more realistic. Furthermore, inverse modelling techniques are applied to gain more insight in the roller properties based on the measurements of the wave height and water level.

The wave-induced computations using the 2DH and 3D approach are also validated using field measurements at Sandy Duck, North Carolina, USA. The data-set consists of both measurements, which are in correspondence with depth-averaged flow velocities and measurements at different vertical elevations to validate the vertical distribution of the current velocity computed using the 3D approach. Both the 2DH and 3D approach corresponds reasonable well with measurements. The longshore flow velocity near the shore is generally overestimated. This is also the case for the wave height computed using the roller model, which shows a systematically overestimation compared with measurements. The advantage of the 3D approach is that it computes a vertical distribution of the currents. This is also validated using the SandyDuck97 measurements and showed that the computed vertical distribution corresponds reasonably well with the computed distributions.

Both the 2DH and the 3D approach can reproduce measured longshore currents and wave heights with reasonable accuracy. The new approach of computing the bed shear stress resolved the dependency on the thickness of the computational layer just above the bed. On the question, which approach performs better, not a conclusive answer can be given. Calibration offers the opportunity to change the outcome significantly. However, since the 3D approach computes a vertical distribution of the currents it could be argued that this approach has an advantage over the 2DH approach when computing sediment transport and morphology. This should be the topic of further research. Furthermore, in further research attention should be paid on the translation of wave forces to a current since some difficulties are found. Furthermore, in the 3D approach no vertical momentum equation is solved since it is assumed that the vertical accelerations are small compared with the gravitational acceleration, reducing the vertical momentum equation to the hydrostatic pressure equation. As waves approach the coast and when waves start breaking, the assumption of hydrostatic pressure might not be valid anymore. Therefore to make fully 3D computations also the vertical momentum equation should be included.

The purpose of Delft3D is amongst others to provide expectations on the morphodynamics of coastal areas. Before the morphodynamics can be computed; first an accurate prediction is needed of the wave height and corresponding hydrodynamics along a coast. Then, the resulting sediment transport is to be computed before the morphology and the morphodynamics of a coast can be determined. A lot of processes need to be determined and since the wave height and resulting hydrodynamics near the coast is at the basic of the morphodynamics, more effort should be made on accurately modelling the wave height and resulting hydrodynamics near a coast.

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1 Introduction

1.1 Problem context

The coast of the Netherlands, but also many other coasts in the world, are subject to increasingly rapid changes, amongst others as a result of sea level changes. The Dutch Rijkswaterstaat, amongst others responsible for sustaining and maintaining the level of the safety and other functionalities of the Dutch coast, increasingly feels the need for a reliable tool to predict future developments of the coast. One of the dominant factors influencing arbitrary coasts are waves.

When waves approach a coastline under an oblique angle, the wave height increases until the moment of incipient breaking at which the organised wave energy is converted into a roller. The roller is a combination of water with entrapped air, and dissipates as it nears the coastline. The release of this wave energy induces nearshore currents which are partly responsible for the transport of sediments alongshore and cross-shore thereby influences the morphology of coastal areas. To make reliable and accurate computations of the coastal morphology it is important to be able to accurately model the wave-induced currents inside the surf zone. Figure 1.1 shows a schematic overview of the processes which have to be determined before the change of the behaviour of a wave influenced coast (morphodynamics) can be computed. It is clearly shown that different processes need to be computed in order to accurately predict the morphodynamics and only an accurate prediction of the morphodynamics of a coast can be determined if each process is computed accurately.

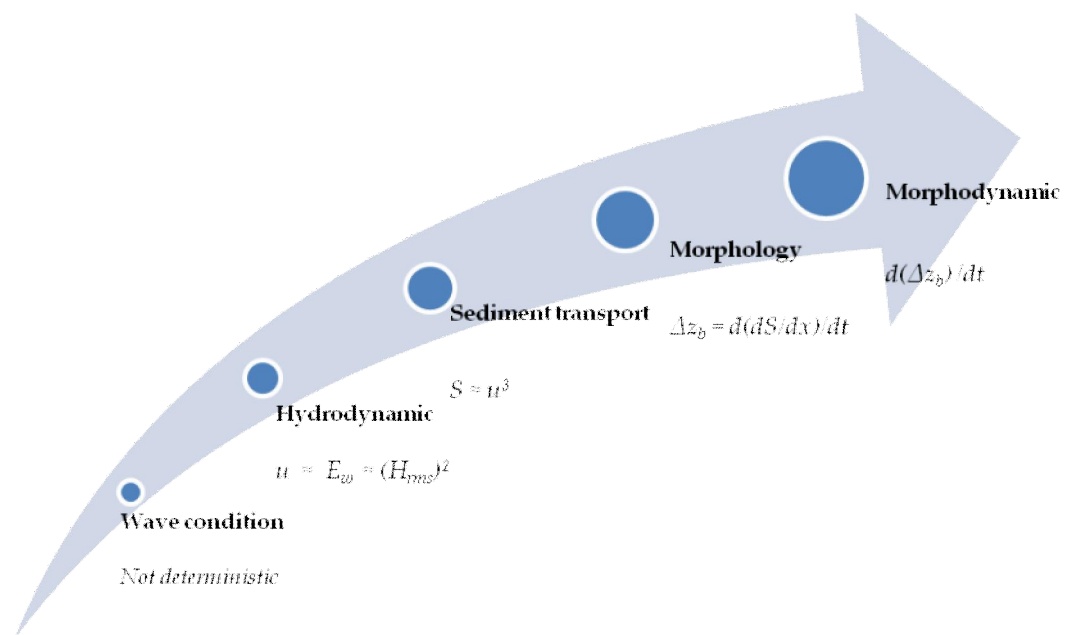


Figure 1.1 Schematic overview of steps needed to determine the change of a coastline

Using the process-based numerical modelling program Delft3D it is possible to compute wave-induced currents inside the surf zone and furthermore to gain insight in the evolution of a coast. Delft3D is already extensively validated using depth-averaged (2DH) approaches however little validation has been done using the fully three-dimensional (3D) approach. A recent study showed that there are still difficulties to accurately predict the behaviour of a coast under the influence of waves using fully three-dimensional computations (Walstra et al., 2008). 3D computations provide the opportunity to determine the vertical distribution of the current velocity which is important for

accurately modelling sediment transport. This study is undertaken to improve the hydrodynamic modelling of the 3D approach in Delft3D.

1.2 Problem description

Predicting the long-term morphology of a straight quasi-uniform coast under the influence of waves by 3D computations using Delft3D shows different results compared to 2DH predictions and reality (Walstra et al., 2008). Walstra et al (2008) found that in 3D computations small-scale disturbances along the coast are created which eventually affect in an unrealistic manner the entire coastline and surf zone. The exact reason for these inconsistencies is not yet fully understood, however there are indications that this is due to the underestimation of the wave-driven currents inside the surf zone. Luijendijk (2007) compared the wave-driven longshore currents predicted by Delft3D in both 2DH and 3D and showed that 3D computations underestimate the longshore currents up to a factor 2 compared with the 2DH computations. Recent studies (Elias et al., 2000; Hsu et al., 2006) show that 2DH computations predict the longshore and cross-shore currents reasonably well. However, in 2DH approaches no vertical distribution of the currents is computed, which is important for suspended sediment related problems and coastal morphology. A logarithmic velocity profile over the vertical is assumed in 2DH, which is for wave-induced currents, especially for cross-shore currents, mostly not the case (Visser, 1991). To take the vertical distribution into account 3D approaches are necessary. 3D approaches are therefore expected to provide more accurate predictions of the sediment transport and coastal morphology. Figure 1.2 again shows the processes which lead to the change of a coastline. However, now the focus area of this study is included. This study only looks into the wave-induced hydrodynamics along a coast in general and inside the surf zone in particular.

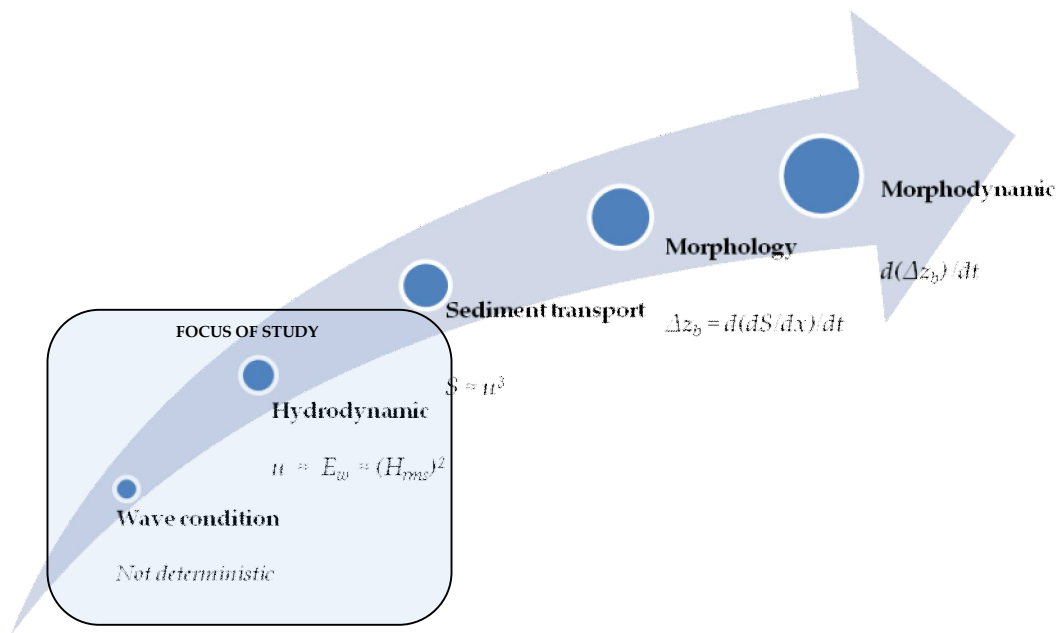


Figure 1.2 Schematic overview of processes leading to the determining the change of a coastline including the focus area of this study

1.3 Objectives and methodology

The objective of this research is to thoroughly assess the ability of Delft3D, both the 2DH and 3D approach, to compute wave-driven longshore currents in the surf zone and to improve Delft3D in this respect. The following research questions are formulated:

- *What are the driving forces of the currents in the surf zone and how are these currents computed for morphological related topics?*
- *What causes the longshore currents computed using the 3D approach to deviate from those computed using the 2DH approach?*
- *What is the performance, of the 2DH and 3D approach in Delft3D, of computing the longshore currents in the surf zone?*

To answer the first research question a literature study is undertaken to determine the forcing that causes and the processes that influence the longshore current in the surf zone. Furthermore, the implementation of these forces in Delft3D, the process-based model used in this study, is examined.

To answer the second research question first the principle differences between the 2DH and 3D approach, in Delft3D, of computing wave-driven currents in the surf zone are determined. With this knowledge a comparison is made between 2DH and 3D computations of wave-driven currents in the surf zone. This is performed for a schematised and idealised quasi-uniform stretch of coast under the influence of waves only. Based on this comparison, model improvements are suggested and implemented.

To answer the last research question first Delft3D is validated by using laboratory measurements, which allows the focus to fully be on wave-driven currents excluding other process such as tide and wind. Model parameters, which have a large influence on the performance of the computation of wave-driven currents, are discussed. Inverse modelling techniques are applied to gain more insight in the translation of the wave forcing to a current. Furthermore, the performance of Delft3D of computing the wave-driven currents in the surf zone is determined by comparing both 2DH and 3D computations with field measurements obtained during the Sandy Duck (North Carolina, USA) measuring campaign in 1997.

For an overview of the different steps taken see Figure 1.3.

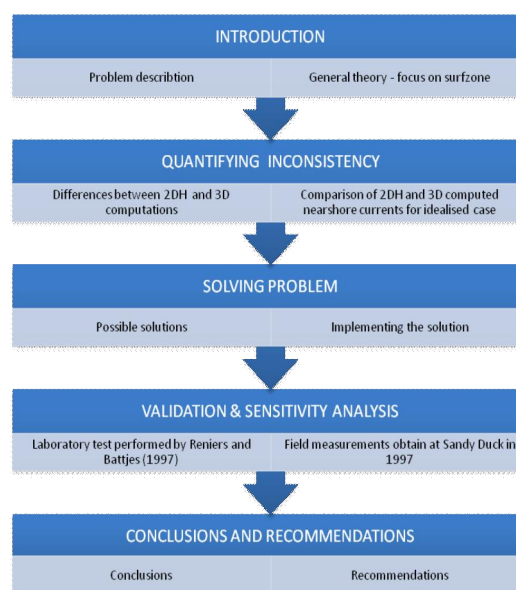


Figure 1.3 Flow-diagram research methodology

1.4 Readers guide

In this research the performance of the wave-induced currents inside the surf zone using the 2DH and 3D approach in Delft3D is examined. The objectives and the framework of this study have been provided in this Chapter. Chapter 2 gives an overview of the relevant processes inside the surf zone which need to be taken into account to accurately model the wave-induced currents. Chapter 3 describes the model Delft3D, which is used in this study, and the differences between the 2DH and 3D approach. In Chapter 4 the results of the 2DH and 3D computed wave-induced currents for a schematised and simplified situation is presented. Furthermore, model improvements are suggested and implemented. In Chapter 5 the model improvements are validated and a model sensitivity analysis is performed using the laboratory measurements obtained by Reniers and Battjes (1997) as a reference. In Chapter 6 Delft3D is assessed using field measurements obtained during the field experiments at Sandy Duck in 1997. Finally, the conclusions on the research objectives and recommendations for future research are provided in Chapter 7.

2 Literature study

2.1 Introduction

In this Chapter the hydrodynamic processes that are present inside the surf zone, i.e. region along the coast where wave breaking occurs, are described. The focus in this study is on quasi-uniform coastlines such as is found along many locations around the globe (Van Rijn et al., 2002). With quasi uniform coastline is meant that the cross-shore bathymetry is close to uniform along the coast i.e. variation of the cross-shore bathymetry along the coast is small.

The surf zone is an important coastal zone since most of the hydrodynamic forces driving the transport of sediments are present inside the surf zone. These forces tend to determine the shape of the coastline. Davis and Hayes (1984) have identified three different types of coastline from the standpoint of the hydrodynamic process affecting a coast;

- Wave-dominated coast
- Tide-dominated coast
- Coast dominated by a balance between waves and tide

In paragraph 2.2 the forces in the surf zone induced by waves are described to gain insight in the important processes and recent efforts to understand these processes. Paragraph 2.3 describes the generation of nearshore currents by waves, tides and wind.

2.2 Waves

2.2.1 General description

Waves are often found to be the dominant force, inside the surf zone, behind longshore currents, sediment transport and coastal morphology (Davis and Hayes, 1984). Water waves in general are the oscillatory movement of a water surface due to wind, storm surges and tides. Waves are often characterized by their wave length (L [m]) or period (T [s]). A distinction can be made between shallow water (short) and deep water waves (long) and is characterized by the ratio of the wave length to the water depth (h [m]) and to the wave height (H [m]). If the $L \ll 20h$ one speaks of deep water waves. Deep water waves are not affected by the bottom in contrast to shallow water waves, therefore the orbital motion of a fluid particles follow a circular path while for shallow water the orbital motion is more an ellipse. Figure 2.1 schematically shows the effect of the bottom on the orbital motion of waves. In this figure it is shown that for deep water (to the right) the orbital motion of the waves does not reach the bottom and therefore the waves are not affected by the bottom. However, if the waves are closer to the shore, the orbital motion of the wave is affected by the bottom; the waves then feel the bottom and therefore the orbital motion of the wave particles become more elliptic.

Long waves are for example tidal waves, storm surges and tsunamis. Short waves are generally generated by wind. The characteristics of these wind waves are determined by the wind speed, the distance over which the wind blows (fetch) and the duration of the wind (Holthuijsen, 2007). Long waves allow the assumption of hydrostatic pressure simplifying the problem significantly.

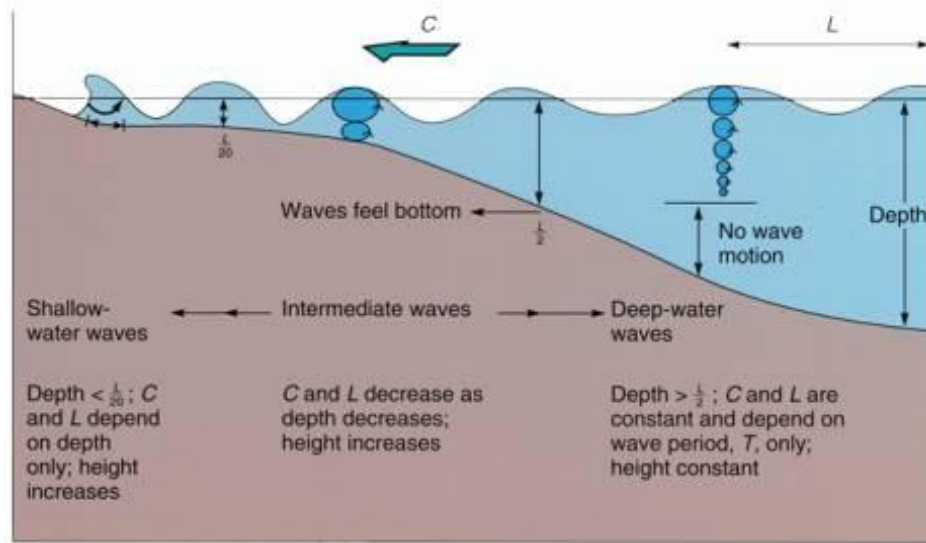


Figure 2.1 Changes in wave orbital motion as depth reduces (Sverdrup et al., 2004)

In the following paragraphs the widely accepted and used linear wave theory and some phenomena which can be explained using this theory are briefly described. For a more detailed and complete description a reference is made to Holthuijsen (2007).

2.2.2 Linear wave theory

The linear wave theory (also called Airy wave theory, the name of the founder of the theory) is an often applied theory by coastal engineers to model a random sea state. The linear theory provides a linearised description of the propagation of waves. In the linear wave theory one of the assumptions made is that the wave amplitude is relative small in relation to the wave length and the water depth, reducing the contribution of non-linear effects to the behaviour of waves. Although for waves in shallow water non-linear processes occur, the linear wave theory is still capable of describing wave phenomena like shoaling and refraction. This paragraph briefly describes the different processes which can be explained using the linear theory and are based on the description of the linear wave theory presented in Holthuijsen (2007).

Wave groups

If two wave trains with different frequencies travel in the same direction they will amplify each other when in phase (i.e. when the crest of both waves occur at the same time) but cancel each other out if out of phase. This will continue until the wave is dissipated as it reaches shallow water. The result is that both wave trains with different frequencies add up to a series of wave groups as can be seen in Figure 2.2. The top figure shows two sinusoidal waves where the second wave (red-line) has a slightly different frequency. At certain moment the crests of both waves coincide and amplify each other, at other moments the crests of the waves are out of phase damping each other out. The bottom figure shows the second wave added to the first wave. Now wave groups (between the black-line) are formed.

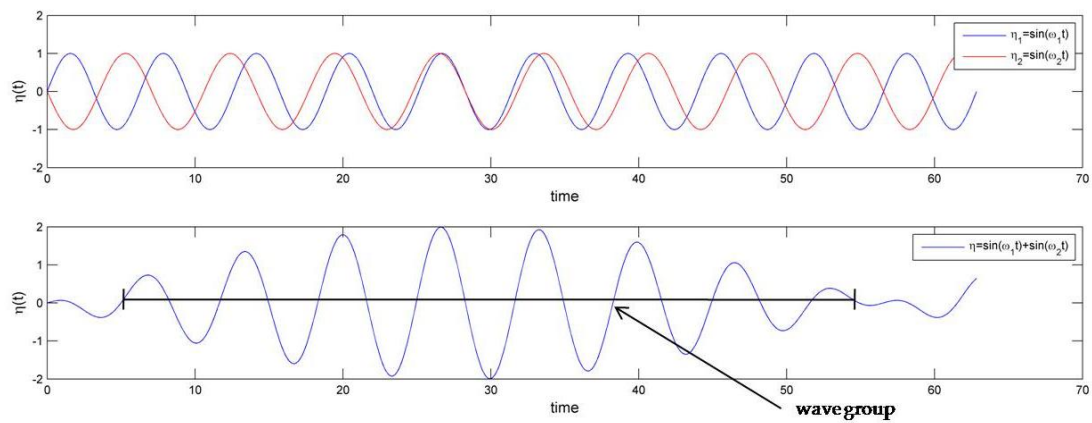


Figure 2.2 Two wave trains added to form a wave group

The velocity of the wave groups is not equal to the velocity of the composing wave trains. The wave group velocity is determined taking into account the dispersion relation for free surface waves (for a full derivation see Holthuijsen (2007)) as:

$$c_g = \frac{\omega_1 - \omega_2}{k_1 - k_2} = \frac{\partial \omega}{\partial k} = nc \quad (2.1)$$

$$n = \frac{1}{2} \left(1 + \frac{2kd}{\sinh(2kd)} \right)$$

In which,

ω	wave frequency $\left(\frac{2\pi}{T} \right)$	$[\text{s}^{-1}]$
k	wave number $\left(\frac{2\pi}{L} \right)$	$[\text{m}^{-1}]$
T	wave period	$[\text{s}]$
d	water depth	$[\text{m}]$

In deep water ($d \gg L$) the n goes to $\frac{1}{2}$ which implies that the group velocity is half the wave velocity. In very shallow water ($d \ll L$) n goes to 1 which implies that the group velocity becomes equal to the wave velocity. This means that the velocity of the individual waves always is larger or equal to the group velocity.

Wave energy

Wave energy can be divided into two parts: the potential energy in a wave and the kinetic energy in a wave. The potential energy represents the vertical change of position of the water particle and the kinetic energy represents the movement of the water particle (Holthuijsen, 2007). The summation of the potential wave energy and the kinetic wave energy gives the total energy in a wave. The wave-induced potential energy is equal to the potential energy of the entire water column in the presence of the waves minus the potential energy of the entire water column in the absence of the waves, according to equation (2.2). The kinetic energy can, assuming sinusoidal free surface waves and using the dispersion relationship, be written as (Holthuijsen, (2007)):

$$\begin{aligned}
 E_{potential} &= \overline{\frac{1}{2} \rho g \eta^2} = \frac{1}{4} \rho g a^2 \\
 E_{kinetic} &= \overline{\int_{-d}^{\eta} \frac{1}{2} \rho u^2 dz} = \frac{1}{4} \rho g a^2
 \end{aligned}
 \tag{2.2}$$

In which,

η	water level with respect to the mean water level	[m]
a	wave amplitude $\left(\frac{1}{2} H\right)$	[m]
u	vector of the water motion	[m/s]

The summation of both potential and kinetic energy gives the time-averaged, wave-induced energy per unit horizontal area:

$$E = \frac{1}{2} \rho g a^2 = \frac{1}{8} \rho g H^2 \tag{2.3}$$

In which,

E	total wave energy per unit of area	[J/m ²]
H	wave height per unit of area	[m]

The wave energy is proportional to the square of the wave height and therefore a second-order property of the wave height. Furthermore, as waves travel across a water surface the wave carry this energy with them. The transport of energy, or energy flux, according to the linear wave theory is defined as:

$$P_{energy} = E c_g \tag{2.4}$$

The wave energy is transported with a velocity equal to and in the same direction as the wave group velocity (c_g).

Shoaling

In general shoaling is the increase of wave height as waves approach a coast. Figure 2.3 schematically shows this process. The wave length reduces and the wave height increases. The phenomenon of shoaling occurs as waves enter shallower water. Consider a situation in which waves propagate with normal incidence (i.e. perpendicular to the coast so no refraction occurs) towards a uniform stretch of coast with a gentle slope. Based on the linear wave theory and assuming longshore bathymetry and no energy dissipation or generation, the wave energy flux towards the coast must remain constant:

$$\frac{d}{dx}(E c_g) = 0 \tag{2.5}$$

This implies that the deep water wave energy flux equals the energy flux near the shore, before any dissipation of wave energy occurs (e.g. due to breaking). This implies that the amplitude of the waves (which is related with the wave energy according to equation (2.3)) varies in cross-shore direction according to:

$$a_2 = a_0 \sqrt{\frac{c_{g,0}}{c_{g,2}}} = a_1 K_{sh} \quad (2.6)$$

In which the zero subscript refers to the deep water value of the parameter. Generally the group velocity decreases as a wave group approaches the coast, thereby, increasing the wave amplitude. Figure 2.3 shows a sketch of the phenomena shoaling.

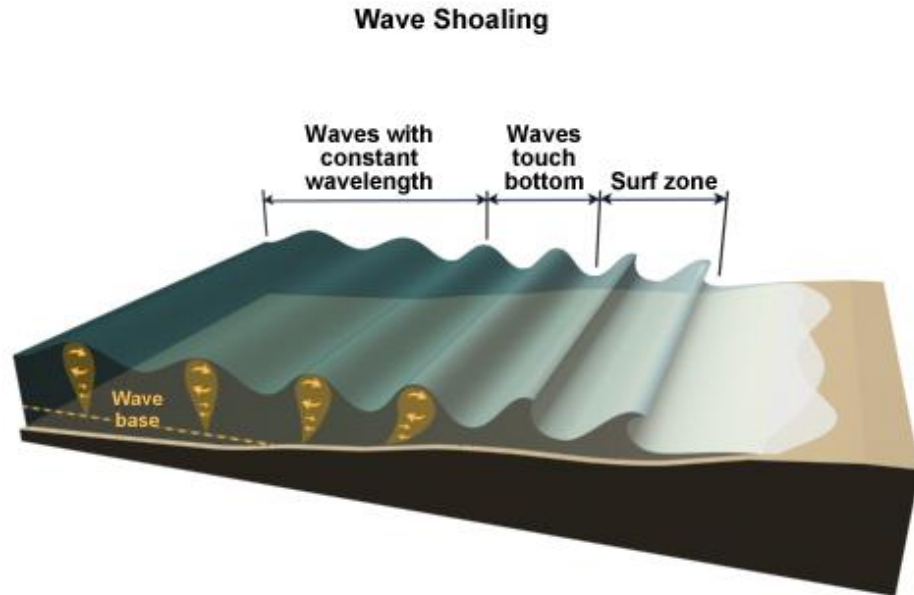


Figure 2.3 Sketch of the phenomenon shoaling [source: Meteorology Education and Training, by the University Corporation for Atmospheric Research (UCAR)]

Refraction

If waves approach a coast oblique then refraction in general is the bending of a wave towards shallow water which is in most cases towards a coast. Figure 2.4 schematically shows the refraction of waves as waves near the coast. Refraction of a wave occurs, since the water depth varies along the crest of a wave for waves propagating towards a random coastline under an angle. This results in a variation of phase speed along the wave crest since the phase speed according to the linear wave theory is related to the water depth according to:

$$c = \sqrt{\frac{g}{k} \tanh(kd)} \quad (2.7)$$

In which,

g gravitational constant [m/s²]

Thus for an increasing water depth the phase speed of a single wave will increase. A variation in phase speed along the crest of a wave turns the wave towards shallower water as can be seen in Figure 2.4.

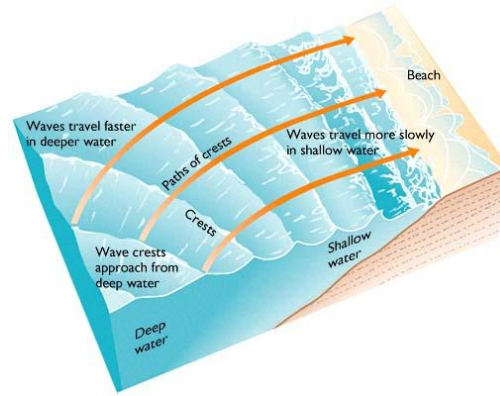


Figure 2.4 Sketch of the phenomenon wave refraction [source: <http://piru.alexandria.ucsb.edu>]

In the absence of any generation or dissipation of wave energy the local value of the wave direction can be computed using Snel's law:

$$\frac{\sin \theta}{c} = \text{constant} \quad (2.8)$$

In which,

c	wave celerity	[m/s]
θ	wave angle	[°]

The angle of propagation θ is taken between the ray and the normal to the depth contours. Refraction is important for wave-induced currents as the longshore current is dependent on the angle of the incoming waves.

2.2.3 Wave breaking

As waves propagate towards the shore the waves deform and at a certain location usually break. The location of incipient wave breaking is determined based on two critical parameters, i.e. the wave steepness (mostly at deeper waters) and the breaker index, which is the ratio between the water depth and the wave height (H/d). As waves approach a coastline the wave height increases and the wave length decreases, in accordance with the linear wave theory. This affects the wave steepness and the breaker parameter. The steepness of the waves is determined by ratio of the wave height to wave length (H/L) and the breaker parameter is determined by the ratio of the wave height to the water depth ($\gamma = H/d \approx 0.7$). Wave breaking occurs if either the limiting value of the wave steepness or the limiting value of the breaker parameter is exceeded. During wave breaking, the organised wave energy is dissipated inducing nearshore currents and a wave induced set up in water level. These wave-induced nearshore currents are important processes in the behaviour of a stretch of coast and are therefore important for coastal morphology.

Already a lot of studies are carried out to determine why and when waves are breaking. Battjes (1974) proposed a parameter to indicate whether or not wave breaking occurs, called the surf similarity parameter:

$$\xi = 2\pi \frac{\frac{H}{\lambda_0}}{\sin^2 \alpha} \quad (2.9)$$

In which,

H	wave height	[m]
λ_0	deep water wave length	[m]
α	beach slope	[-]

Wave breaking occurs if $\zeta > 1$.

For the breaker parameter, besides a constant ratio between the wave height and the water depth, Battjes and Stive (1985) proposed a breaker parameter that relates to the deep water wave steepness (S_d):

$$\gamma = 0.5 + 0.4 \tanh(33s_d) \quad (2.10)$$

Ruessink et al (2003) proposed an empirically derived parameter for wave breaking which is not cross-shore constant but depth varying:

$$y = 0.76kd + 0.29 \quad (2.11)$$

As mentioned earlier, due to wave breaking, the organised wave energy is dissipated in the form of a (roller) bore. Due to this dissipation of energy nearshore currents are generated. This energy dissipation causes so-called radiation stresses. The radiation stress is an important parameter since the radiation stresses drive longshore currents. The next paragraph describes the principle of radiation stress in more detail.

2.2.4 Radiation stress

The theory of radiation stress was first described in a series of papers by Longuet-Higgins and Stewart (1962) (1963) (1964). The basic principle of this theory is that waves exert a force on vertical surfaces. The cause of this force is the fact that waves carry momentum and the rate of change of this momentum, which occurs if a wave is reflected of a vertical surface, results in a force. The radiation stress is, according to Longuet-Higgins and Stewart (1964), defined as; the excess flow of momentum due to the presence of the waves.

As the rate of change of momentum, or the momentum flux, is equal to a force, the principle component of the radiation stress (S_{xx}) can be defined as the mean value of the total flux of horizontal momentum across a constant plane (integrated between bottom $z = -h$ and the free surface $z = \zeta$) minus the mean flux in the absence of the waves. This can be written, according to Longuet-Higgins and Stewart (1964), as:

$$S_{xx} = \overline{\int_{-h}^{\zeta} (p + \rho u^2) dz} - \int_{-h}^0 p_0 dz \quad (2.12)$$

In which,

S_{xx}	radiation stress in the direction of wave propagation	[N/m]
p	hydrostatic pressure of water	[N/m ²]
ρu^2	flux of horizontal momentum	[Nm]
p_0	hydrostatic pressure of water in rest	[N/m ²]

Integrating (2.12) leads to the magnitude of the radiation stress in the direction of wave propagation, which is mainly dependent on the wave energy and thus, the wave height:

$$S_{xx} = \left(\frac{1}{2} + \frac{2kd}{\sinh(2kd)} \right) E = \left(2n - \frac{1}{2} \right) E \quad (2.13)$$

In which n is as defined in (2.1) and E as defined in (2.3). Similar expressions can be set up to obtain the tensor of the radiation stress in the other directions (S_{yy} , S_{xy} and S_{yx}). Figure 2.5 shows the different tensors of the radiation stress for waves approaching a coastline (right grey vertical balk) under an angle. The principle components, which act in the direction of wave propagation, are translated to normal stresses (S_{xx} and S_{yy}) and to shear stresses (S_{xy} and S_{yx}).

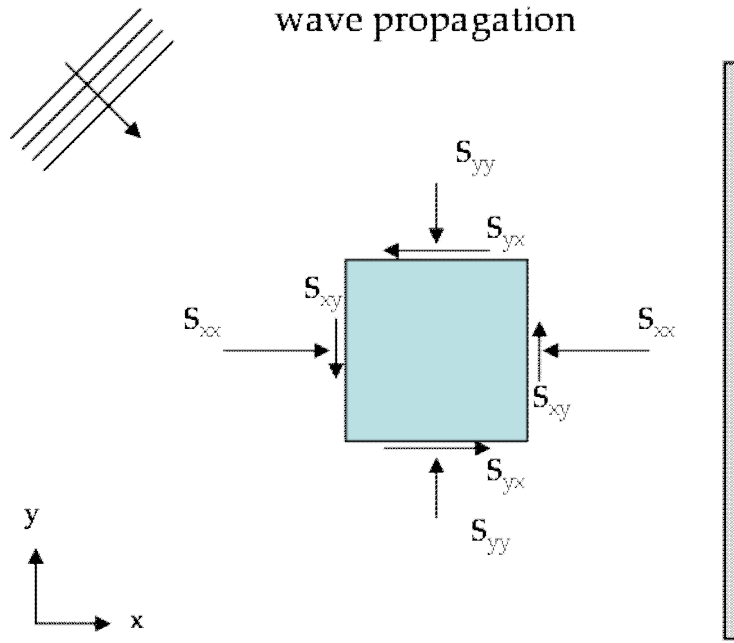


Figure 2.5 Radiation stress tensors for oblique incident waves approaching a coastline

The normal forces and shear stresses are determined, according to Longuet-Higgins and Stewart (1964):

$$\begin{aligned} S_{xx} &= \left(n - \frac{1}{2} + n \cos^2 \theta \right) E \\ S_{yy} &= \left(n - \frac{1}{2} + n \sin^2 \theta \right) E \\ S_{xy} &= n \cos(\theta) \sin(\theta) E \\ S_{yx} &= n \sin(\theta) \cos(\theta) E \end{aligned} \quad (2.14)$$

These are the components of the radiation stress due to oblique incident waves. The radiation stress is important since a cross-shore gradient in the S_{xy} and S_{yx} and alongshore gradient in the S_{xx} part of the radiation stress is the cause of a longshore current. A cross-shore gradient in the S_{xx} part causes a wave-induced set-up.

2.3 Wave-induced currents

2.3.1 Introduction

Obliquely incident waves or swells approaching a straight coastline induce a mean current parallel to the coastline (Longuet-Higgins and Stewart, 1960). These longshore currents cause the alongshore transport of sediments and thereby influence the coastal morphology. Longuet-Higgins (1970) derived a formulation of the longshore current based on his earlier research on radiation stress caused by waves (Longuet-Higgins and Stewart, 1964).

2.3.2 Longshore current

If wave approach a alongshore uniform coastline under an angle a longshore current is generated. As waves approach the coast the energy in a wave is reduced due to wave breaking. The reduction in wave energy causes a reduction in the wave generated radiation stress. Consider an area inside the surf zone as schematically shown in Figure 2.6, the cross-shore reduction of wave energy results in a smaller radiation stress shoreward. The force induced by the cross-shore varying radiation stress on the water body is given by:

$$\begin{aligned} F_x &= \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \\ F_y &= \frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \end{aligned} \quad (2.15)$$

In which,

$F_{x,y}$ Radiation stress induced force [N/m²]

The cross-shore difference in radiation stress is compensated by a flow-induced bed shear stress, according to the quadratic friction law:

$$\tau_b = \rho u_*^2 \quad (2.16)$$

In which,

τ_b bed shear stress [N/m²]

u_* friction velocity [m/s]

As the longshore current compensates the cross-shore gradient in the radiation stress, the magnitude of the longshore current is dependent on amount of wave energy dissipation and the roughness of the bottom. The rougher the bottom the lower the longshore current has to be to compensate for the gradient in the radiation stress.

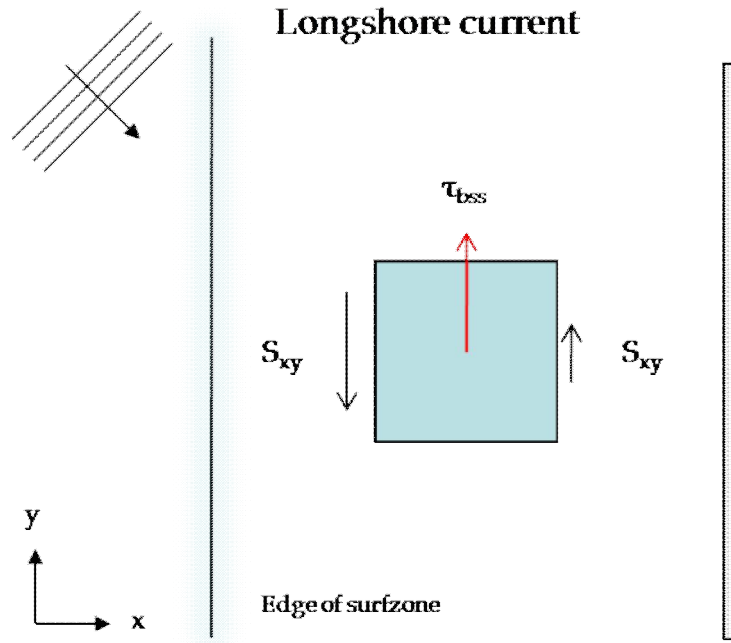


Figure 2.6 Radiation stress induced longshore current

Outside the surf zone no wave energy dissipation due to wave breaking occurs and therefore the wave energy and thus the radiation stress remain constant. Therefore, no gradients in the radiation stresses occur. However, still a longshore current can be generated just outside the surf zone due to the lateral exchange of momentum. This is an extensively research topic in coastal engineering. Battjes (1975) argued that the horizontal exchange of momentum, induced by wave breaking, is dependent on the amount of wave energy which is dissipated; according to:

$$v_t = h \left(\frac{D}{\rho} \right)^{\frac{1}{3}} \quad (2.17)$$

In which,

v_t	horizontal eddy viscosity	[m ² /s]
h	total water depth	[m]
D	dissipation of wave energy	[N/ms]

Due to the horizontal exchange of momentum the cross-shore distribution of the longshore current resembles the distribution shown in Figure 2.7.

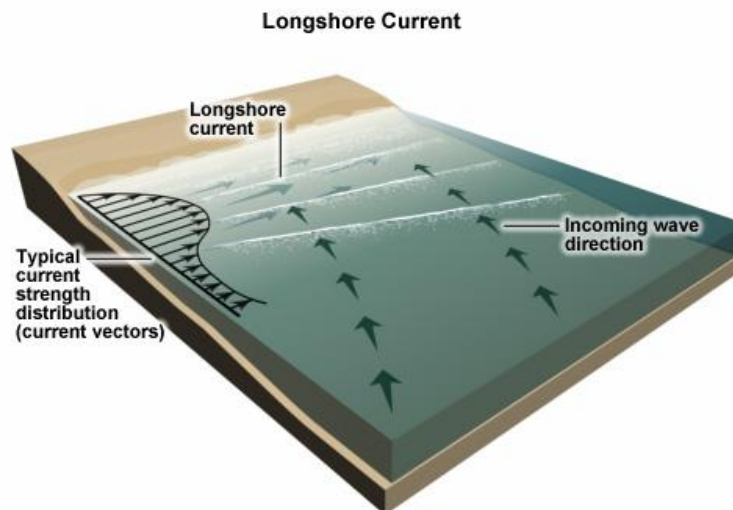


Figure 2.7 Sketch of wave-induced longshore currents [source: Meteorology Education and Training, by the University Corporation for Atmospheric Research (UCAR)]

2.3.3 Cross-shore current

As waves propagate towards a stretch of coast the forward and backward displacement in the water induced by non-breaking waves is nearly in balance. However, there is a residual flux of water in the direction of wave propagation, which occurs mostly in the wave crest. As wave breaking occurs the landward flux of water is enlarged due to the additional flux of aerated water in the form of a roller. The presence of a shoreline and assuming longshore-uniform conditions this mean landward discharge in the upper part of the water column must be compensated by a offshore directed return-flow (i.e. the undertow) in the lower part of the water column (Dally, 2005).

The wave-induced cross-shore current is important for sediment transport since this current induces a seaward directed bed shear stress component which determines the rate of cross-shore sediment transport.

2.4 Tide-induced currents

Although tide-induced currents are not included in this research it is briefly explained for the sake of completeness. Tidal-induced currents can be an important process inside the surf zone and therefore is important for coastal engineers.

Besides waves also the tide induces a force on the water affecting the current velocity of the water near a coast. Tide is the cyclic horizontal and vertical movement of a water body which is the results of the gravitational force acted by the moon and the sun on the earth's water body. The magnitude of the effect of this force is different all over the globe and dependent on several aspects (e.g. regional bathymetry). The tide is deterministic in contrast to wind-induced waves and therefore the tidal forcing can if the different constituents are determined based on measurements always be predicted. The tide can induce relative large forces on a coastline and can in some cases be dominant over wave-induced forces, as described in more detail by (Davis and Hayes, 1984).

2.5 Wind-induced currents

As for tide-induced also wind-induced currents is briefly described for the sake of completeness since it can have a large influence during storm conditions.

As a body of air travels over a body of water a resulting shear stress induces a force which results in the moving of the upper part of the water in roughly the same direction as the wind. The vertical distribution of the velocity induced by wind is quite different from tide- or wave-induced forces. Wind-induced currents can have an effect on the residual longshore current during storm events, however; often the wind-induced contribution to the currents can be neglected.

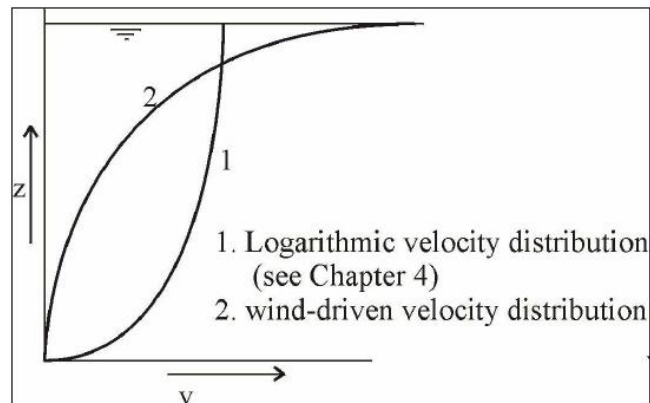


Figure 2.8 Vertical distribution of wind-induced currents compared with a logarithmic vertical distribution (Van de Graaff, 2006)

3 Delft3D

In this study the process-based numerical model Delft3D is used to compute the wave-driven currents inside the surf zone. Delft3D is a modular build numerical modelling program in which the different modules interact with each other. Each module focuses on a different process; flow of water, waves, sediment transport, morphological behaviour, ecology and water quality. The focus of this study is on the differences found between the 2DH and 3D computations of wave-driven currents in the surf zone. Therefore, only the Flow- and Wave-module are used in this study.

To determine why these differences occur it is important to understand how the model performs the computations. This Chapter provides a general description of Delft3D in which briefly the mathematical background of Delft3D, the different modules used in this study and some assumptions, which are made in Delft3D, are described (paragraph 3.1). Furthermore, the differences between the 2DH and 3D approach are explained (paragraph 3.2).

3.1 General description

3.1.1 Build-up of modules

In this study only the Flow and Wave modules in Delft3D are used. These modules in Delft3D can either be coupled – ‘online’ or uncoupled – ‘offline’. In the ‘online’ mode at user defined intervals there is an interaction between the Flow- and Wave-module. The Wave-module recalculates the wave conditions using the hydrodynamics from the Flow-module at that certain interval. The newly updated wave conditions then are used as input for the Flow-module (see Figure 3.1). In the ‘offline’-mode there is no interaction between the Wave and the Flow-module. The Wave-module computes the wave conditions which are used as input in the Flow module (red-line).

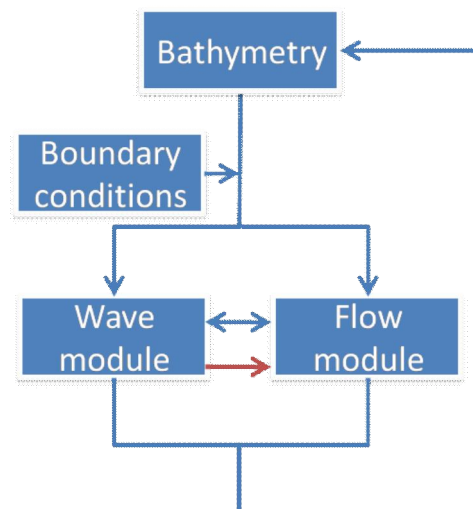


Figure 3.1 Delft3D computation scheme

For some processes (e.g. wave deformation due to current and rip-currents) the online coupling between both modules is important since these processes are the consequence or are enhanced by the wave-current interaction.

3.1.2 Flow-module

The Flow-module determines the hydrodynamics in Delft3D and describes the two-dimensional (2DH) or three-dimensional (3D) unsteady flow phenomena. These are situations where the horizontal scale (length and time) are larger than the vertical scale (depth), for instance in coastal areas, shallow seas, estuaries, lagoons and rivers. A detailed description of the hydrodynamic formulas, assumptions, boundary conditions and numerical schemes used in Delft3D can be found in (Lesser et al., 2004) and the Flow manual (Deltares, 2007a). In this paragraph only a brief description of the applied equations is presented.

Delft3D-Flow solves the Navier Stokes equations for an incompressible fluid under the shallow water and the Boussinesq assumptions. The vertical accelerations are neglected by assuming them small compared to the gravitational acceleration. Therefore, reducing the vertical momentum equation to the hydrostatic pressure equation. The system of equations consists of the:

- Continuity equation
- Horizontal equation of motion

The continuity equation is given by,

$$\frac{\partial \zeta}{\partial t} + \frac{\partial(d + \zeta)u}{\partial x} + \frac{\partial(d + \zeta)v}{\partial y} + \frac{\partial \omega}{\partial z} = 0 \quad (3.1)$$

and the momentum equation in x-direction,

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{\omega}{h} \frac{\partial u}{\partial z} = -g \frac{\partial \zeta}{\partial x} + f v + \nu_H \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + \frac{1}{h^2} \frac{\partial}{\partial z} \left(\nu_v \frac{\partial u}{\partial z} \right) - \frac{g u \sqrt{u^2 + v^2}}{h C^2} \quad (3.2)$$

and the momentum equation in y-direction,

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{\omega}{h} \frac{\partial v}{\partial z} = -g \frac{\partial \zeta}{\partial y} - f u + \nu_H \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \frac{1}{h^2} \frac{\partial}{\partial z} \left(\nu_v \frac{\partial v}{\partial z} \right) - \frac{g v \sqrt{u^2 + v^2}}{h C^2} \quad (3.3)$$

In which,

ζ	water level according to reference level	[m]
d	depth	[m]
h	total water depth ($h = d + \zeta$)	[m]
u	flow velocity in x-direction	[m/s]
v	flow velocity in y-direction	[m/s]
ω	flow velocity in z-direction	[m/s]
f	Coriolis parameter	[1/s]
ν_H	horizontal eddy viscosity	[m ² /s]
ν_v	horizontal eddy viscosity	[m ² /s]
C	Chézy-coefficient	[m ^{1/2} /s]

When using the 3D approach, no vertical momentum equation is solved since the assumption is made that the vertical accelerations are small compared to the gravitation acceleration. The vertical velocity is computed from the continuity equation. In the 2DH approach the terms containing the vertical coordinate (z), the vertical flow velocity (ω) and the vertical eddy viscosity (ν_v) are not taken into

account. These terms only influences the vertical distribution of momentum. Therefore, in fact, the same set of equations is solved in the 2DH approach as in the 3D approach only the vertical distribution of momentum is not computed using the 2DH approach. The numerical implementation of the abovementioned equations in the Flow-module is briefly described in Appendix A.2. The Flow manual (Deltares, 2007a) provides a detailed description of the physical background, boundary conditions and numerical implementation of the Flow-module.

3.1.3 Wave-module

The Wave-module is used to compute the evolution of wind-generated waves in coastal waters (e.g. estuaries, tidal inlets, etc.). The Wave-module computes wave propagation, wave generation by wind, non-linear wave-wave interactions and dissipation for deep, intermediate and finite water depths. In this study the wave model SWAN is used. SWAN, which is an acronym for **S**imulating **W**aves **N**earshore, is based on the discrete spectral action balance equation and is fully spectral in all directions and frequencies. This implies that short-crested random wave fields that propagate simultaneously from all directions can be computed. Since this research focuses on the 2DH and 3D computations of wave-induced flow the Wave-module is not described in detail. A brief description is presented in Appendix A.3. The Wave manual (Deltares, 2007b) provides a detailed description of the physical background and the numerical implementation of SWAN.

In this study the Roller model according to Nairn et al (1990) is used to delay the transfer of wave energy to the current. Recent studies showed that including the Roller model showed better results compared with measurements (Hsu et al., 2006; Reniers and Battjes, 1997). In Appendix B a more detailed description is given on the physical background of the Roller model.

3.2 Differences 2DH and 3D approach

3.2.1 Introduction

The main difference between 2DH and 3D approach is that vertical layers are included to account for vertical variations. The vertical momentum equation in both cases (2DH and 3D) reduced to the hydrostatic pressure equation by neglecting the vertical accelerations, i.e. assuming that the vertical accelerations are small compared to the gravitational acceleration. For the computation of the bed shear stress in the 2DH approach the vertical distribution of the longshore current is assumed to be logarithmic. In Figure 3.2 an example of a logarithmic velocity distribution is given. The velocity is zero at z = the bottom level and maximum at z = 0 (the water level).

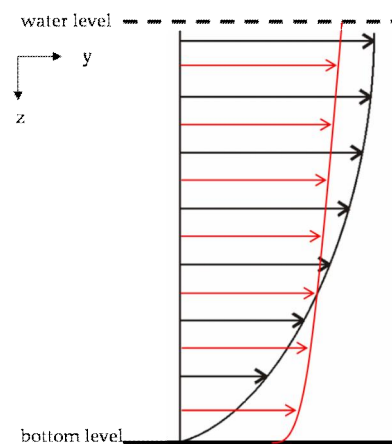


Figure 3.2 Example of a logarithmic velocity distribution (black-line) and a more uniform distributed distribution (red-line)

In reality, due to the presence of wave breaking the velocity profile may deviate from a logarithmic velocity distribution, since wave breaking-induced turbulence strongly enhances vertical mixing (Svendsen and Lorenz, 1989). The red-line in Figure 3.2 shows an example of a more uniform distribution of the current. In Delft3D, 3D modelling includes some important processes, which influences the vertical distribution of the current velocity. Wave-breaking induced production of turbulent kinetic energy, streaming and Stokes-drift are included in the 3D approach. These processes are responsible for the vertical distribution of the longshore and cross-shore flow to deviate from the standard logarithmic profile. These processes are included aiming at a realistic simulation of the vertical velocity profile. A good representation of the vertical current profile can only be obtained with a 3D model since a 3D approach includes an extra (vertical) dimension and thereby computes the velocity at different elevations in the vertical.

The vertical distribution of the longshore current that results from the 3D calculation is of particular importance for current-related suspended load in the longshore direction. The abovementioned differences between 2DH and 3D approach are briefly described in the next sections.

3.2.2 Vertical layers

The vertical layers applied in the 3D approach are in the case of this study σ -layers which imply that the individual layers are a percentage of the total water depth. Figure 3.3 shows an example of sigma-layers. As the thickness of the layers is a percentage of the water depth the individual vertical layers follow the depth contour of the bottom. In the figure this can be seen as the horizontal lines are following the bottom (grey area).

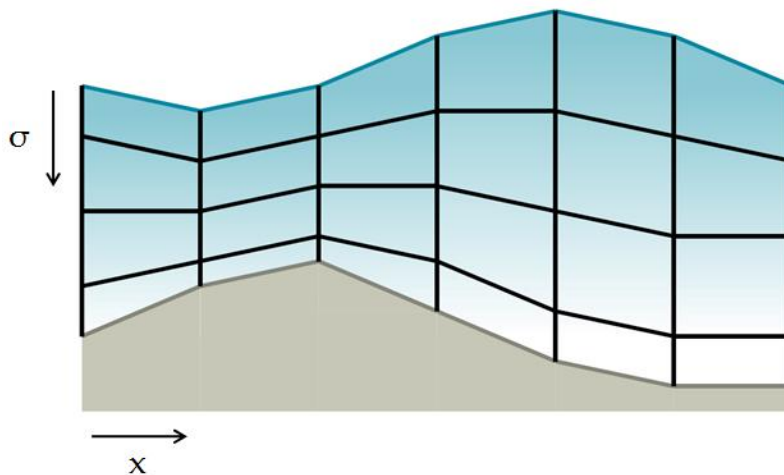


Figure 3.3 Schematic example of sigma-layers (Ullmann, 2008)

Some parameters can be varied when including these vertical layers. The amount of vertical layers, the vertical distribution of the layers and the variation factor of the distance between mutual subsequent layers can be varied. A small layer thickness can be desired at specific locations in the vertical if certain important processes occur at that specific location. A higher resolution in the vertical layers increases the accuracy. In example; if waves would play an import role thin vertical layers near the water surface (wave breaking) and near the bottom (wave-induced bottom friction) would be required to accurately take these processes into account. The right figure of Figure 3.4 shows an example of a log-log distribution with thin layers at the top and bottom and thicker layers in the middle. The left figure shows a linear distribution of the vertical layers, which implies that the thickness of subsequent layers is equal. To reduce the thickness of the layers in the top and / or bottom for a linear layer

distribution; the amount of vertical layers has to increase. Increasing the amount of vertical layers per definition increases the computational time. To reduce the computational time the distribution of the vertical layers can be changed.

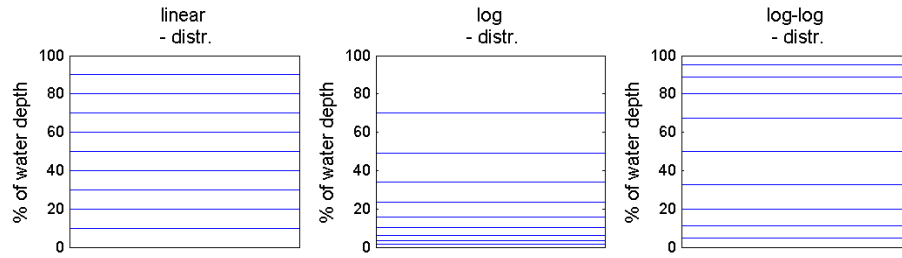


Figure 3.4 Example of the different vertical distribution types for 10 vertical layers

3.2.3 Wave induced turbulence

Wave actions (e.g. white-capping or wave breaking) increase the amount of vertical mixing. To include wave-induced enhancement of vertical mixing, the assumption is made that the decay of organised wave energy is transferred into turbulent kinetic energy (Walstra et al., 2001). The production of this turbulent kinetic energy is then included in the turbulence model as source term. In Delft3D the two main sources of decay of wave energy, due to wave breaking and bottom friction, are included. Both sources of turbulent kinetic energy are included in the turbulence closure model in Delft3D (Walstra et al., 2001). White-capping and wave breaking induced turbulent kinetic energy are applied in the top boundary layer. The bottom friction induced turbulent kinetic energy (i.e. due to the oscillatory wave motion) is applied in the bottom boundary layer (Figure 3.5). The wave-breaking induced production of turbulent kinetic energy occurs near the mean water level (MWL) and is assumed to linear decrease over the depth and is zero at half the wave height. The bottom friction induced production of turbulent kinetic energy occurs near the bottom and is also assumed to decrease linear, for an increasing water depth and is assumed to be zero at the edge of the wave boundary layer (δ).

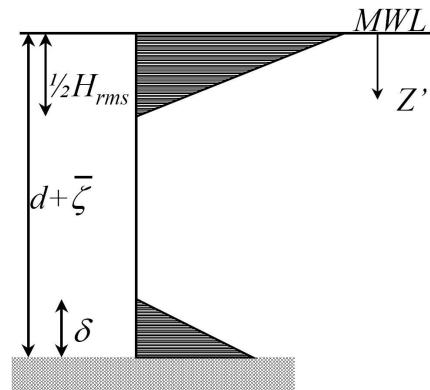


Figure 3.5 Vertical distribution of the production of kinetic energy

The wave-induced turbulence is added to the turbulence models (k - ϵ) as a source term for turbulent energy. The expressions for the turbulent kinetic energy distribution due to wave breaking and bottom friction are, respectively, given by:

$$P_{kw}(z') = \frac{4D_w}{H_{rms}} \left(1 - \frac{2z'}{H_{rms}} \right), \text{ for } z' \leq \frac{1}{2} H_{rms} \quad (3.4)$$

$$P_{kw}(z') = \frac{2D_f}{\delta} \left(1 - \frac{d + \zeta - z'}{\delta} \right), \text{ for } d + \zeta - \delta \leq z' \leq d + \zeta \quad (3.5)$$

In which,

D_w	dissipation due to wave breaking	[N/ms]
D_f	dissipation due to bottom friction	[N/ms]
z'	vertical coordinate	[m]
δ	thickness of the wave boundary layer	[m]

The thickness of the wave boundary layer is determined according to;

$$\delta = 0.36 \left(\hat{A}_\delta \right) \left(\frac{\hat{A}_\delta}{k_{s,w}} \right)^{\frac{1}{4}} \quad (3.6)$$

In which,

$k_{s,w}$	Wave related roughness	[m]
$\hat{A}_\delta$	Peak orbital excursion at the bed, according to:	

$$\hat{A}_\delta = \frac{T_p \hat{U}_\delta}{2\pi} \quad (3.7)$$

In which,

T_p	Peak wave period	[s]
$\hat{U}_\delta$	Peak orbital velocity near the bed	[m/s]

3.2.4 Streaming

Streaming is taken into account as a time averaged shear stress which is the result from the phase-difference between the horizontal and vertical orbital velocity. They are not exactly 90 degrees out of phase. The magnitude of streaming is closely related to the dissipation of wave energy due to bottom friction, which is dependent on the orbital velocity. This implies that streaming strongly depends on the wave height. The dissipation of wave energy due to bottom friction is calculated in Delft3D according to;

$$D_f = \frac{1}{2\sqrt{\pi}} \rho_0 f_w u_{orb}^3 \quad (3.8)$$

In which f_w denotes the friction factor according to the Flow-manual (2007a) determined by:

$$f_w = \min \left\{ 0.3, 1.39 \left(\frac{A}{z_0} \right)^{-0.52} \right\} \quad (3.9)$$

$$A = \frac{u_{orb}}{\omega}$$

In which,

Z_0	bottom roughness height	[m]
u_{orb}	orbital velocity due to waves	[m/s]

The orbital velocity is calculated according to;

$$u_{orb} = \frac{1}{4} \sqrt{\pi} \frac{H_{rms} \omega}{\sinh(kh)} \quad (3.10)$$

In which,

H_{rms}	root mean squared wave height	[m]
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However, Delft3D actually uses a fixed value for f_w of 0.01 (Delft3D source code: taubot.f90).

Streaming can have a relative large influence if the waves are relatively high. Inside the surf zone where wave breaking occurs the process of streaming is negligible compared to wave breaking induced energy dissipation. However, just outside the surf zone, where the waves are not breaking, streaming can influence the vertical distribution of the current. As this study focuses on the wave-driven currents inside the surf zone, it is expected that streaming will have little influence.

3.2.5 Stokes drift and mass flux

Stokes drift is the averaged velocity of a fluid particle in surface waves. Fluid particles in surface waves describe an orbital motion in which the net horizontal movement is not zero. A particle at the top of the orbital that is under the wave crest moves slightly faster than it does at the bottom of the orbital under the wave trough. The Stokes drift velocity is always in the wave propagation direction. The mean drift velocity is a second order quantity of the wave height. The Stokes drift leads to the following additional mass-fluxes (integration of Stokes drift velocity components over the wave-averaged total water depth):

$$\begin{aligned} M_x^S &= \frac{E}{\omega} k_x \\ M_y^S &= \frac{E}{\omega} k_y \end{aligned} \quad (3.11)$$

Where,

M^S	Mass-flux	[kgm/s]
-------	-----------	---------

The Stokes drift velocity varies over the depth since the mass-fluxes are integrated over the wave-averaged total water depth. The implementation of the Stokes drift in 2D is depth-averaged given by:

$$\begin{aligned} U^S &= \frac{M_x^S}{\rho_0(d + \zeta)} \\ V^S &= \frac{M_y^S}{\rho_0(d + \zeta)} \end{aligned} \quad (3.12)$$

In which,

$(d + \zeta)$	total water depth	[m]
U^S, V^S	Stokes drift induced velocity	[m/s]

For the 3D implementation the Stokes drift is computed by the linear wave theory:

$$\vec{u}^S = \frac{\omega k a^2 \cosh(2kH)}{2 \sinh^2(kH)} (\cos \phi, \sin \phi)^T \quad (3.13)$$

The angle between the current and the waves is computed from the mass-fluxes:

$$\phi = \tan^{-1}(M_x^S, M_y^S) \quad (3.14)$$

3.2.6 Bed shear stress

Delft3D computes the bed shear stress in both 2DH and 3D computations based on the assumption of a logarithmic velocity profile. The bed shear stress, in 2DH, due to currents only is determined according to the quadratic friction law:

$$\vec{\tau}_b = \frac{\rho g \vec{U} |\vec{U}|}{C_{2D}^2} \quad (3.15)$$

In which,

$ \vec{U} $	magnitude of the depth-averaged velocity	[m/s]
C_{2D}	Chézy roughness coefficient	[m ^{0.5} /s]

The Chézy roughness coefficient is a direct input parameter in Delft3D according to either one of three formulations (i.e. Chézy, Manning's or White Colebrook's formulation). In 3D the bed shear stress is computed according to (vector notation is excluded for simplicity and clarification):

$$\tau_{b_{3D}} = \frac{\rho g u_b |u_b|}{C_{3D}^2} = \rho u_* |u_*| \quad (3.16)$$

In which,

u_b	velocity in the first computational layer above the bed	[m/s]
C_{3D}	Chézy roughness coefficient	[m ^{0.5} /s]
u_*	friction velocity	[m/s]

The friction velocity is computed, assuming a logarithmic velocity profile, according to:

$$u_* = \frac{u_b K}{\ln \left(1 + \frac{\Delta z_b}{2z_0} \right)}$$

In which,

κ	Von Karman constant	[-]
Δz_b	thickness of the layer just above the bed	[m]
z_0	bed roughness height	[m]

A 3D – Chézy roughness coefficient is used to account for the fact that the velocity in the layer just above the bed, instead of the depth-averaged velocity, is used to compute the bed shear stress. When assuming a logarithmic velocity profile in the layer just above the bed the 3D Chézy coefficient can be written as:

$$C_{3D} = \frac{\sqrt{g}}{\kappa} \ln \left(1 + \frac{\Delta z_b}{2z_0} \right) \quad (3.17)$$

The bed roughness height is the height at which u_b theoretically goes to zero. The roughness height is determined based on the 2DH Chézy coefficient:

$$z_0 = \frac{H}{e^{\frac{\kappa C_{2D}}{\sqrt{g}}} - 1} \quad (3.18)$$

3.2.7 Conclusion

Both the 2DH and 3D approach solve approximately the same momentum and continuity equations. In the 3D approach also momentum is transferred vertically and a vertical velocity component is computed. In the 3D approach Delft3D takes some processes into account aiming at realistically describing the vertical distribution of the currents. Besides forces and processes are implemented at the location in the vertical where they actually take place. In the 2DH approach no wave-breaking enhanced vertical mixing is included. Using the 3D approach a vertical distribution of the velocity is computed which is of particular importance for current related suspended sediment load. Both the 2DH and 3D approach assume a hydrostatic pressure and therefore neglect vertical accelerations.

In the following paragraphs the 2DH and 3D approach of computing the wave-driven currents are compared for an idealised case.

4 Idealised case

Results Chapter

- Wave-induced longshore current inside the surf zone is underestimated for small angles of incident waves in 3D independent on the chosen wave climate. The relative error decreases as the angle of incident waves increases, the absolute difference remains roughly the same
- For wave-driven longshore currents; reducing the thickness of the computational layer just above the bed by results in a further underestimation of the wave-driven longshore currents inside the surf zone
- Gradient-induced flow shows no dependency on the vertical layer distribution
- Bed-shears stress computations are dependent on the thickness of the layer just above the bed, assuming a logarithmic distribution of the current velocity profile and therefore causes the computation of the wave-induced longshore current to be dependent on the vertical layer distribution
- The layer dependency can be overcome by using the velocity in a fixed point in the vertical, which is independent on the thickness of the bottom computational layer. The velocity in the layer above the edge of the wave-boundary layer is suggested to use

4.1 Introduction

In this Chapter the differences in the currents computed for an idealised and schematised case using the 2DH and 3D approach are described. This case concerns an alongshore uniform coast profile with two breaker bars in cross-shore direction. A breaker bar is a submerge shoaling which is the result of wave breaking induced transport of sediment towards deeper parts of the beach. In time this process results in a submerge bar. This idealised coast will only be influenced by waves.

In paragraph 4.2 the model set-up, boundary conditions and forcing are described. Furthermore, the influence and representation of the different parameter settings in Delft3D are briefly explained. In paragraphs 4.3 and 4.4 the results of the comparison between 2DH and 3D computations are elaborated by comparing computed currents in 2DH and 3D with each other for an idealised situation. Furthermore, model improvements are suggested in paragraph 4.5 to increase the accuracy of the 3D approach.

4.2 Model set up

To compare 2DH and 3D computed wave-induced currents a uniform coast profile is used based on the profile of the Egmond coast in the Netherlands, which has two breaker bars. A cross-shore section of the model used is shown in Figure 4.1. The area is characterized by a gentle slope seaward, followed by a seaward breaker bar (high energy waves break here first) and the trough between the first and second breaker bar. The second breaker bar is primarily formed due to low energy waves breaking near the shore transporting sediment towards deeper parts. Due to these breaker bars three-dimensional flow-patterns occur as can be seen in Figure 4.2. In this figure right side is the coast and the blue arrows denote the flow velocity vectors; these vectors point downward between the two breaker bars creating circular flow patterns. In reality these three-dimensional flow patterns also most likely occur. The 2DH approach is unable to reproduce this variation over the vertical and the vertical currents and therefore a three-dimensional approach is necessary. This emphasizes the importance of three-dimensional hydrodynamic calculations. Furthermore, tidal and wind forcing are neglected in this model since the goal is to look at wave-induced currents. The model is alongshore uniform to get an alongshore uniform flow field allowing a good comparison between 2DH and 3D computations (Figure 4.2).

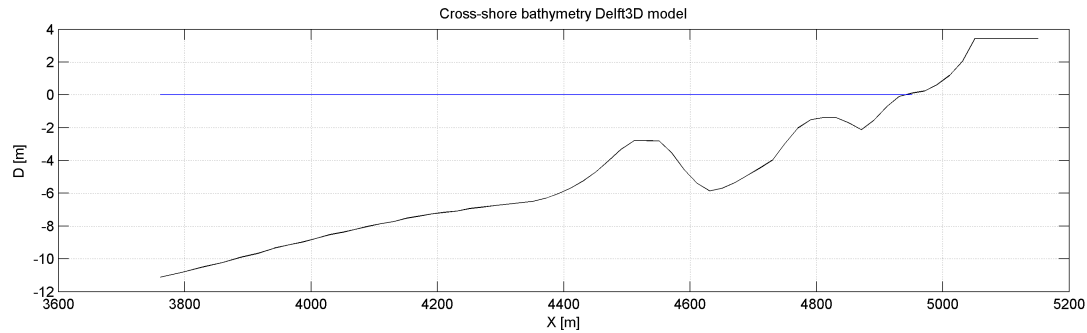


Figure 4.1 Cross-shore bathymetry of the model in Delft3D

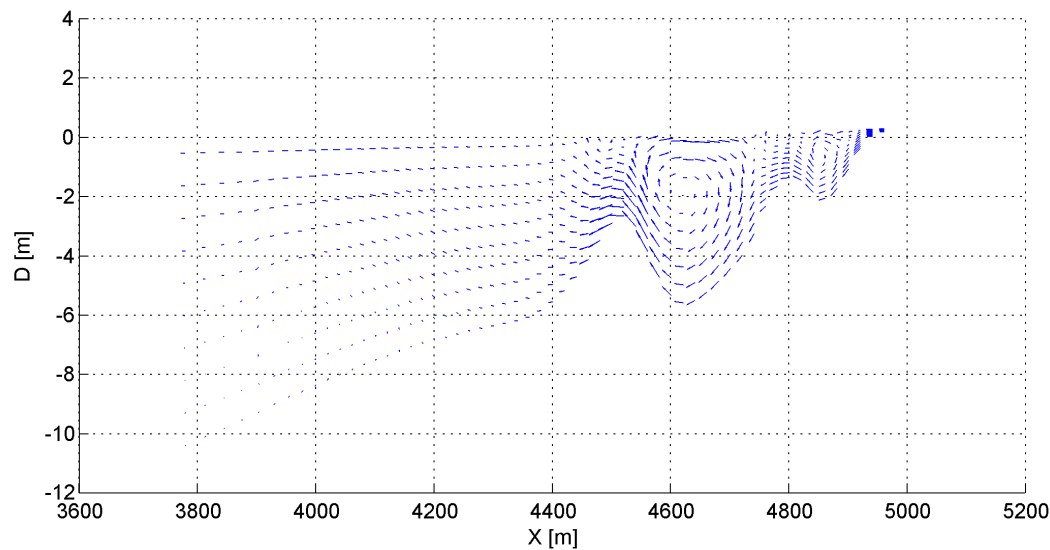


Figure 4.2 Flow velocity vectors for H_s is 3 meter, T_p is 8 seconds and θ_{wave} is 5°

Most of the standard settings in Delft3D are used. Table 4.1 gives an overview of the standard and applied Delft3D settings. Each parameter is briefly described below the table.

Table 4.1 Settings Delft3D – Uniform Egmond model

Parameters	Delft3D Settings	
	Default Settings	Used Settings
Simulation time (min)	-	240
Time step (min)	-	0.25
Number of vertical layers (-)	1	1 (2DH) , 10, 15, 30, 40, 50
Layer distribution type	linear	linear / log-log
Reflection parameter α (s^{-2})	0	1000
Roughness – Chézy ($m^{0.5}/s$)	65	65
Background horizontal visc. (m^2/s)	1	1
Threshold depth (m)	0.1	0.2
Smoothing time (min)	60	60
Roller model	no	yes
Cstbnd	no	yes
Gamdis	0.55	acc. to: (Ruessink et al., 2003)
F_lam (breaker delay)	0	0
Slope of roller (β)	0.1	0.1

The simulation time determines the period over which the simulation is run. Since the forcing but also the bathymetry is stationary an uniform outcome over time is expected. However, the model has to spin up before this equilibrium situation is achieved; therefore the simulation time has to be long enough to let initial disturbances propagate out of the model.

The time step determines the interval of the computations. In case of this study the time step is 0.25 minutes and the simulation time is 240 minutes. This means that 960 computations are made. Furthermore, the time step is an important parameter for the numerical stability of the computation. The simulation should satisfy the Courant criteria as is described in Appendix A 2.2.

If the number of vertical layers exceeds one the 3D approach is used.

The reflection parameter (α) is a parameter that lets initial disturbances propagate out of the model quickly, decreasing the spin-up time of the model, by making the open offshore boundaries less reflective for disturbances at the start of the computation.

Background horizontal eddy viscosity represents complicated hydrodynamic phenomena, which in 2DH are the 2DH – turbulence and dispersion coefficient and in 3D the 2DH turbulence. Varying this parameter influences the horizontal exchange of momentum.

The threshold depth is the depth above which a grid cell is considered to be wet. The threshold depth must be defined in relation to the change of the water depth. Since in this comparison study the tide is excluded, thus a constant water level a value of 0.1 would be sufficient. However, due to the inclusion of the roller model the threshold depth is set at 0.2 (for explanation of this value see below on the roller model).

The smoothing time is the time interval used at the start of a simulation to achieve a smooth transition between the initial conditions and boundary conditions. A smoothing time of 60 minutes, the default value, is chosen however a smaller value could be sufficient since the initial condition is equal to the offshore boundary condition.

The roller model is used during these calculations. In principle the roller model delays the transfer of wave energy to a force by first transferring the wave energy to roller energy which propagates on top of the wave as a bore before dissipating via turbulence in heat. Thus, the roller model causes the location of the maximum longshore current to be shifted towards the coast. A study at Duck and Santa Barbara, USA (Hsu et al., 2006) has shown that including the roller model the velocity peak shifts more towards the coast which is in agreement with the measurements. However, including the roller model unrealistic high velocities can occur close to the shore. The explanation given by Hsu et al is that the amount of roller energy dissipation is too high resulting in too high velocities. In Delft3D, the roller forcing is neglected at a depth of 2 times the threshold depth. Increasing this threshold depth to 0.2 meters prevents these unrealistic high currents. For a more detailed described of the roller model see Appendix B.

The keyword 'Cstbnd' can be used to avoid the generation of an artificial boundary layers along the boundary of the model. This is done by switching off the advection terms at the boundaries containing normal gradients.

Gamdis (γ_{diss}) is a parameter that defines the maximum wave height that can occur at a given water depth. The expression of (Ruessink et al., 2003), which is a cross-shore varying breaker index according to formula (2.11) is used.

The breaker delay (F_{lam}) is an optional feature that delays the breaking of the waves (Reniers et al., 2004a; Roelvink, 2003). It uses a weighted average of the local water depth up to the water depth a user-defined number of wavelengths seaward, to compute the energy dissipation due to wave breaking. As the depth mostly increases seaward the point of incipient energy dissipation is moved shoreward. However, the breaker delay is implemented to provide better morphological results while the hydrodynamics results often become worse (personal communication: (Walstra, 2009)).

The slope of the roller (β) determines how fast roller energy is dissipated. A fixed value of 0.1 is found to give good results (Nairn et al., 1990).

To determine the sensitivity of the computed longshore currents to some parameter settings in Delft3D some parameters are varied. Different forcing is applied to determine the sensitivity of Delft3D to the forcing. The parameters varied are presented in Table 4.2.

Table 4.2 Varying parameters Delft3D

Parameters	Delft3D
	Settings
Wave angle	5, 15, 30, 45, 60, 75 °
Wave height (H_s)	1 – 3 m
Wave period (T_p)	5 – 7.9 s
Vertical layers	10, 20, 30, 50
Distribution type	linear / log-log

The boundary conditions for waves are chosen such to represent a relative calm wave condition and a storm condition. The variation in wave angle is to validate and quantify one of the conclusions of Luijendijk (2007) that the difference between 2DH and 3D increases for a smaller angle of incident waves. Furthermore, different wave conditions and vertical layer distributions are chosen to determine if the differences between 2DH and 3D are dependent on the wave climate and model settings.

The results of the 2DH and 3D computations are discussed in the next paragraph.

4.3 Model results

4.3.1 Introduction

In this paragraph the results of the comparison between 2DH and 3D computed wave-driven currents inside the surf zone are described. The wave conditions and model settings are varied, as mentioned in the previous paragraph. The goal is to quantify the difference between 2DH and 3D computations and to determine what causes the disagreement.

4.3.2 Forcing

To quantify the differences between the 2DH and 3D computed currents the hydrodynamic forcing should be equal for both computations. At first only the different wave conditions are compared and for the 3D computations 10 layers linearly distributed over the vertical (i.e. each 10 % of water depth thick) are applied. Table 4.3 shows the wave conditions used.

Table 4.3 Wave conditions used for the comparison between 2DH and 3D computed longshore currents

Boundary condition	Hydrodynamic condition	
	H_s (m)	T_p (s)
Wave condition 1 (calm)	1	5
Wave condition 2 (storm)	3	8

Delft3D computes the waves in 2DH and 3D using SWAN and the roller model. Both are not directly dependent on whether 2DH or 3D computations are made. Only the interaction between the flow and wave computations might induce differences. Figure 4.3 shows the wave energy computed by 2DH and 3D for wave condition 1 (left figure) and wave condition 2 (right figure) for a small wave angle ($\theta_{\text{wave}} = 5^\circ$). The left side is the seaward side of the model and right the landward side. Wave energy can be converted to a wave height according to equation (2.3). The differences between 2DH and 3D computed wave energy are negligible, which is according to the expectations.

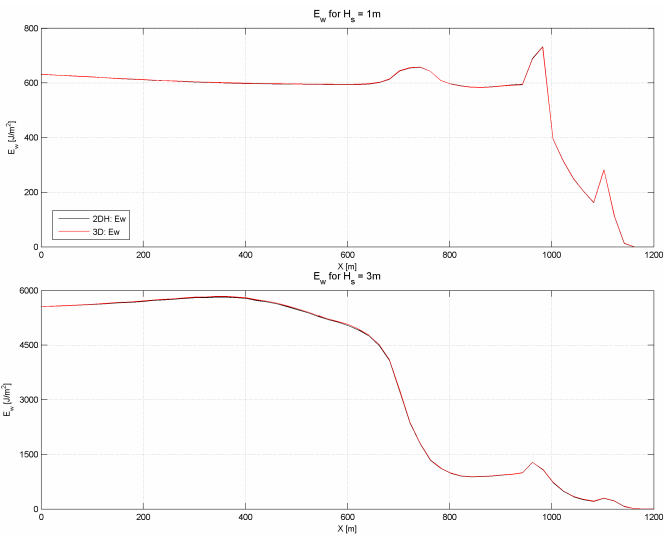


Figure 4.3 Cross-shore distribution of the wave energy for wave condition 1 (top figure) and wave condition 2 (bottom figure). Black line is the 2DH and red line the 3D approach

The water level set up computed using the 2DH and 3D approach, is shown in Figure 4.4. Small differences are found between the 2DH and 3D approach. However, these differences are remarkable since the forcing is exactly the same in both approaches.

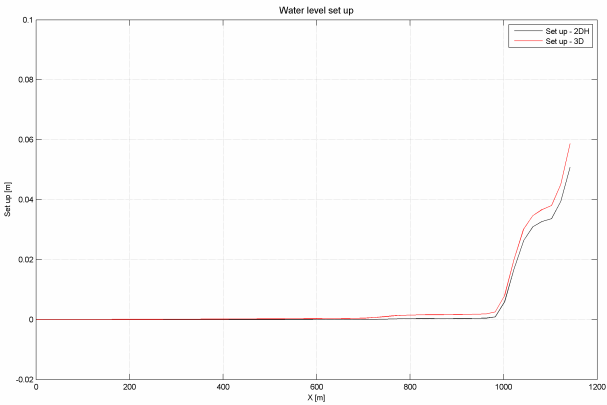


Figure 4.4 Cross-shore distribution water level set up for wave condition 1. Black line is the 2DH and red line the 3D approach

4.3.3 Cross-shore distribution wave-driven currents

To obtain an insight in the differences between the 2DH and 3D computed currents the cross-shore distribution of the wave-driven longshore and cross-shore currents in the surf zone are compared.

Longshore current

The cross-shore distribution of the surf zone currents computed by Delft3D in 2DH and 3D is shown in Figure 4.5 and Figure 4.6 for both wave conditions (see Table 4.3). The top left figure of Figure 4.5 shows that the longshore current computed by 3D in the surf zone is underestimated compared to the 2DH computed current. However, at a certain distance from the coast the 3D computed longshore current is larger than in 2DH. For clarification; the coast is situated at the right hand-side of the figure. If the angle of incident waves increases the same overestimation outside the surf zone is found (right figure of Figure 4.5). This figure furthermore shows that the difference between the 2DH and 3D computed wave-driven longshore current becomes significantly smaller for a larger wave angle. The reason for the dependency on the wave angle is not yet understood, however, Luijendijk (2007) suggested that it might be due to numerical sensitivities at small wave angles.

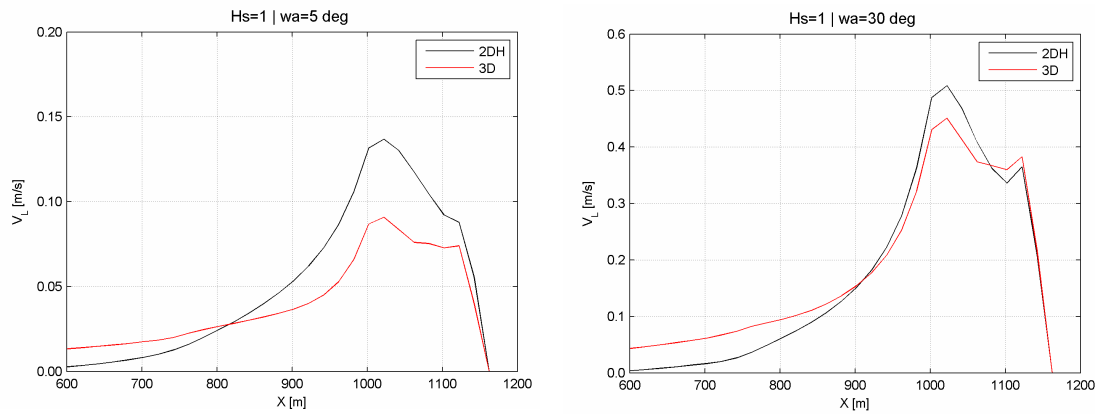


Figure 4.5 Cross-shore distribution of the depth-averaged longshore current for wave condition 1 and a small (left figure) and large (right figure) angle of incident waves

For the computations with wave condition 2 (Figure 4.6) similar discrepancies are found. As for wave condition 1 also for wave condition 2 a significant underestimation of the maximum longshore current for small angles of the waves is found. For larger wave angles the relative difference reduces. The same conclusion can be drawn for wave condition 2.

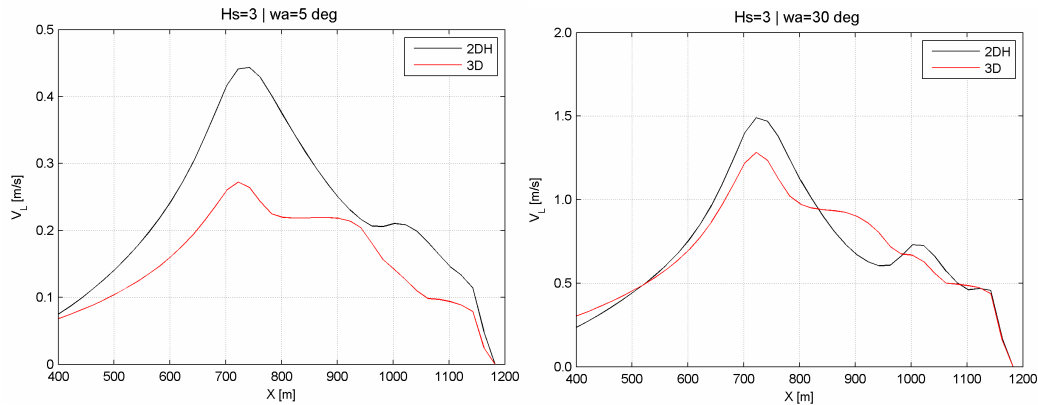


Figure 4.6 Cross-shore distribution of the depth-averaged longshore current for wave condition 2 and a small (left figure) and large (right figure) angle of incident waves

The overestimation of the 3D computed longshore currents outside the surf zone is due to the process streaming. A 3D computation is made excluding the process streaming and showed a significant reduction in the overestimation of the seaward computed longshore current, see Figure 4.7. As mentioned in paragraph 3.2.4 streaming is not taken into account in the 2DH approach. Streaming is modelled as a time-averaged shear stress caused by the orbital velocity. Inside the surf zone the effect of streaming sharply reduces as the wave height decreases, while outside the surf zone, where no wave breaking occurs, the relative contribution of streaming to the longshore current increases. This can be seen in Figure 4.7. Inside the surf zone streaming has a relative small contribution to the current velocity in comparison to contribution outside the surf zone. Since this research primarily focuses on the currents in the surf zone the effect of streaming is disregarded but is included in the computations since it also included in the default settings of Delft3D for 3D computations.

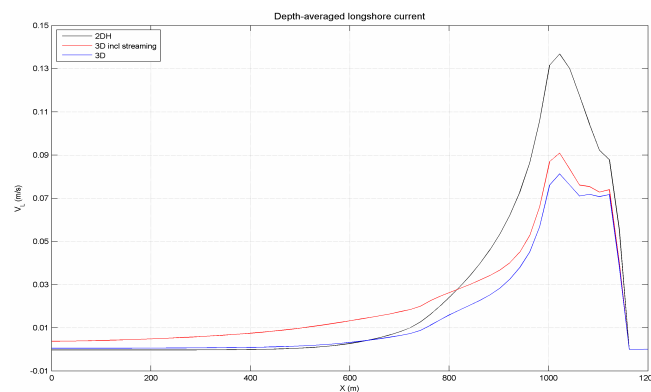


Figure 4.7 Simulation using 3D approach including (red-line) and excluding (blue-line) the process streaming

Cross-shore current

The cross-shore distribution of the cross-shore current computed by Delft3D in 2DH and 3D is shown in Figure 4.8. In contrast to the longshore current, the cross-shore currents computed in 3D differ little from those in 2DH. Small changes between 2DH and 3D occur at the locations where the cross-shore current is largest and larger changes near the coast. Figure 4.9 shows the computed cross-shore current for wave condition 2, which shows similar results as for wave condition 1. The differences in water level set up, as shown in Figure 4.4, can explain the differences found between the 2DH and 3D computed cross-shore currents.

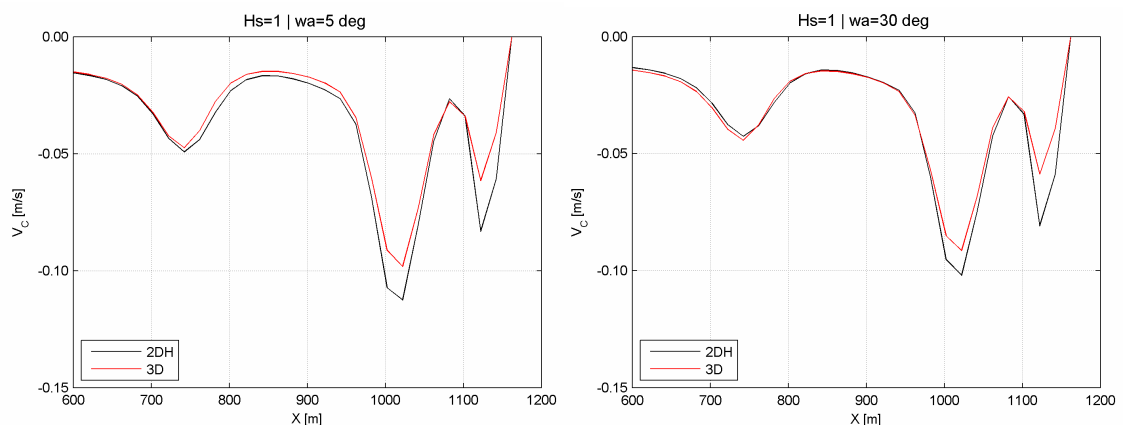


Figure 4.8 Cross-shore distribution of the cross-shore current for wave condition 1 and a small (top left figure) and large (bottom left figure) angle of incident waves

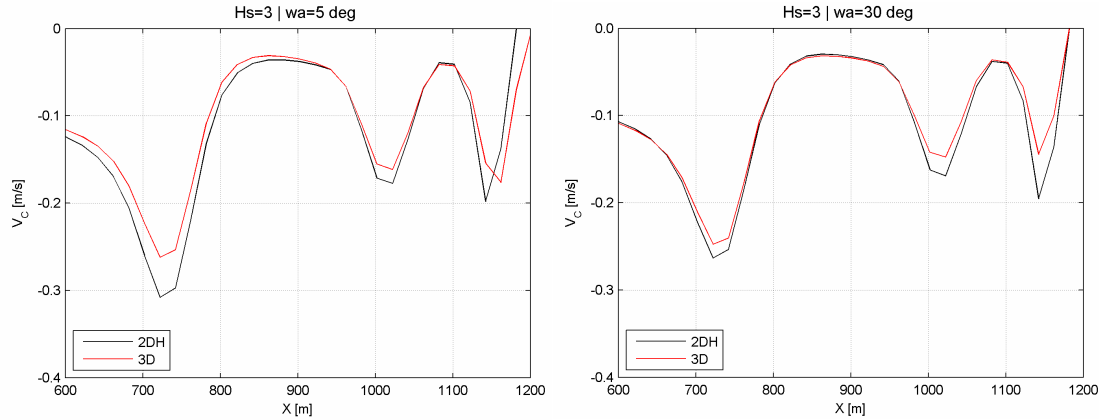


Figure 4.9 Cross-shore distribution of the depth-averaged cross-shore current for wave condition 2 and a small (top left figure) and large (bottom left figure) angle of incident waves

4.3.4 Longshore current – wave angle

Luijendijk (2007) already mentioned that the differences between 2DH and 3D are largest for small angles of incidence waves. To further quantify this phenomena, the computed maximum longshore current in 2DH and 3D for both wave conditions and for the different wave angles are compared.

Figure 4.10 shows that the computed maximum longshore current in 3D for wave condition 1 ($H_s = 1\text{m}$, $T_s = 5\text{s}$) is almost a factor two smaller in 2DH for a small wave angle. When increasing the wave angle this difference reduces. However, the absolute difference does not change significantly until the angle of incident waves exceeds 45 degrees. For the wave condition 2 ($H_s = 3\text{m}$, $T_s = 8\text{s}$) the same differences between 2DH and 3D computations are found (Figure 4.11). The relative difference between 2DH and 3D is comparable for both wave conditions. For a small wave angle the relative difference between 2DH and 3D computations is large while the absolute difference is approximately the same for an increasing wave angle.

Based on the above findings it could be argued that the wave condition has little effect on the discrepancy between the 2DH and 3D computed wave-driven currents inside the surf zone.

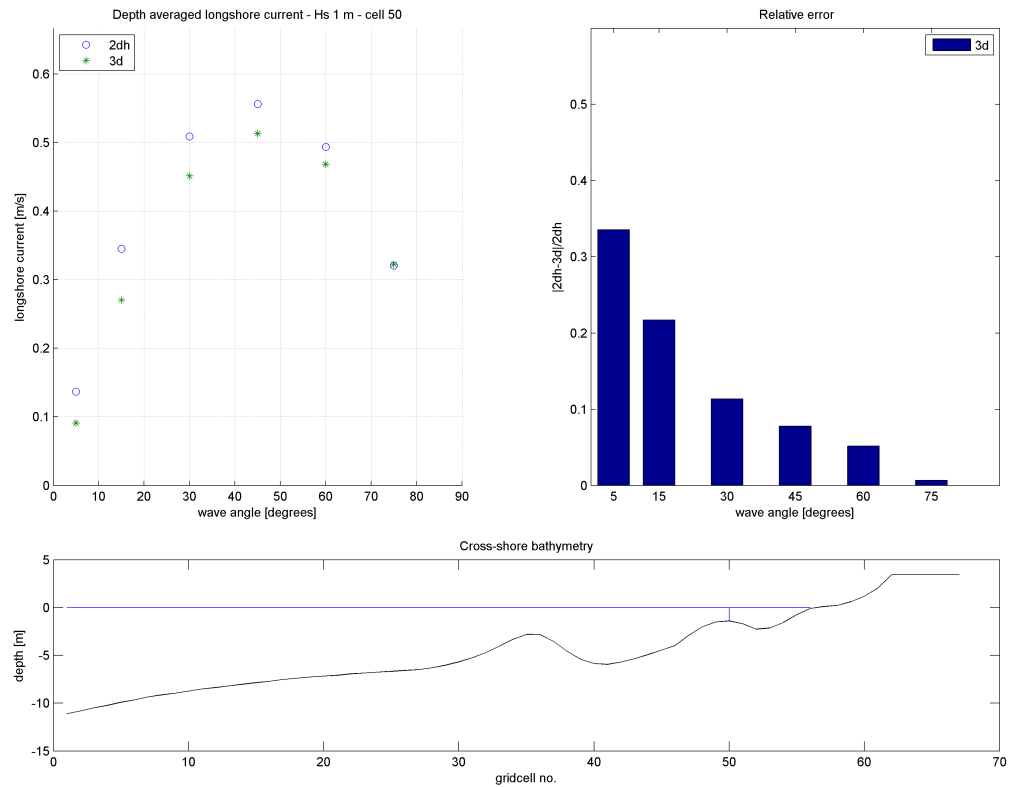


Figure 4.10 Depth averaged longshore current varying over the angle of incidence waves for $H_s = 1m$, $T_s = 5s$. This is for the location where the maximum longshore current occurs.

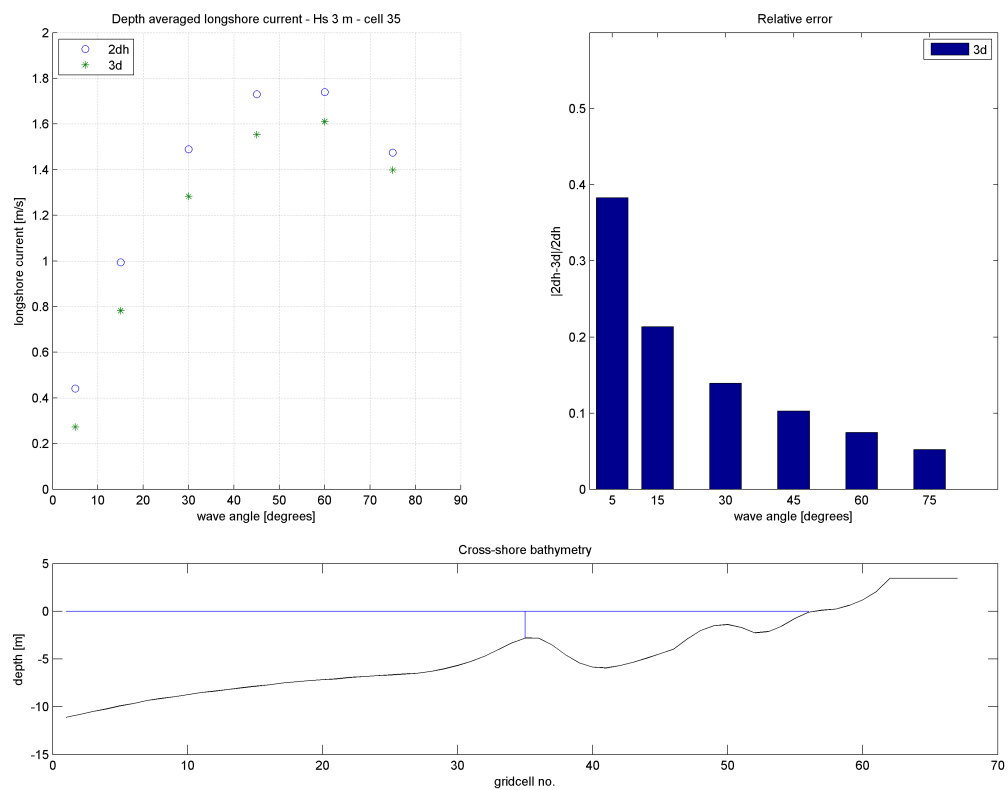


Figure 4.11 Depth averaged longshore current varying over the angle of incidence waves for $H_s = 3m$, $T_s = 7.9s$. This is for the location where the maximum longshore current occurs.

4.3.5 Effect of vertical layers

As mentioned in paragraph 4.1 the 3D simulations are conducted using a user-defined number of vertical layers. The thickness of the individual layers can be varied. These simulations are made to determine the influence of the number of layers and the vertical distribution of these layers on the wave-driven longshore current. Increasing the number of vertical layers implies increasing the resolution of the calculations in the vertical and thereby theoretically increasing the accuracy.

Figure 4.12 shows the results of the maximum longshore current (cell 50) for different wave angles and different vertical layer distributions. This figure clearly shows that increasing the number of vertical layers affects the longshore current significantly. For all wave angles the difference between 2DH and 3D increases as the number of vertical layers increases. It seems that the computed maximum longshore current in 3D is more dependent on changes in the model set up than on changes in the external forcing. The absolute difference between the computed maximum longshore current and 2DH does not significantly change if the wave angle increases. However, the absolute difference does increase if the number of vertical layers increases.

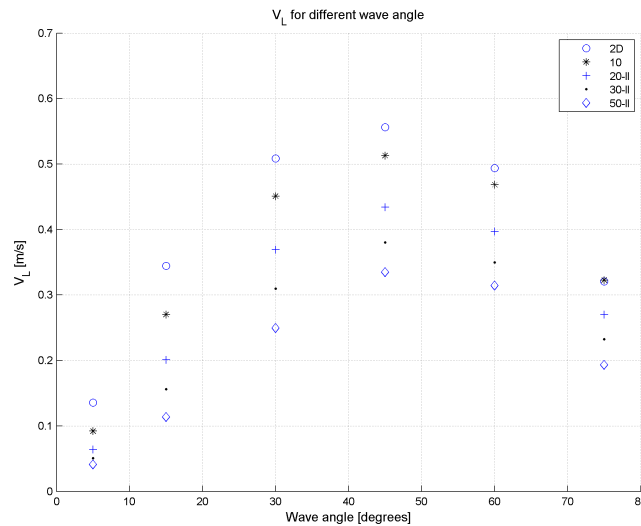


Figure 4.12 Depth-averaged longshore current varying over the wave angle of incidence waves for wave condition 1 and 5 different vertical layer distributions (2DH linear 10, 20,30,50 log-log distribution)

To obtain better insight in the effect of applying more vertical layers on the computed maximum longshore current the vertical distribution of the current is further discussed. The left figure of Figure 4.13 shows the computed vertical distribution of the longshore and cross-shore currents for different number of vertical layers (10, 20, 30 and 50 log-log distributed layers). The top-left figure is the vertical distribution of the cross-shore current and the top right figure is the vertical distribution of the longshore current. The bottom figure shows the cross-shore distribution of the depth-averaged longshore current. The different layer distributions have the same variation factor between subsequent layers, only the number of layers is varied. The vertical distribution of the cross-shore velocity does not significantly change for an increase of the number of vertical layers. However, the longshore current does significantly change. Increasing the number of layers reduces the longshore current up to a factor of 2 (Table 4.4).

The reason that the cross-shore current differs little while the longshore current differs significantly compared with 2DH is due to the method of computing the longshore current. The longshore current is determined by the roller induced force in the longshore direction, which is balanced by a longshore current induced bed shear stress. According to the Flow-manual (2007a) the computation of the bed

shear stress includes the thickness of the bottom layer. Thereby, the bed shear stress computation is dependent on the number of vertical layers applied. The cross-shore current is determined by the wave and roller induced mass-flux towards the coast. The mass-fluxes take place at the top of the water column and are compensated by an opposite directed current near the bottom. Therefore the cross-shore current is in fact a balance between the wave and roller induced mass-flux and the return current. The return current is also affected by the roughness of the bottom, which might explain the differences near the bottom and top boundary.

To verify if the thickness of the bottom layer influences the underestimation of longshore current in the 3D approach several simulations are made with different number of vertical layers but with the same thickness of the layers near the bottom and near the surface. The right figure of Figure 4.13 shows the results of these computations. The difference between the vertical distributions of the longshore current is significantly reduced compared with the left figure of Figure 4.13.

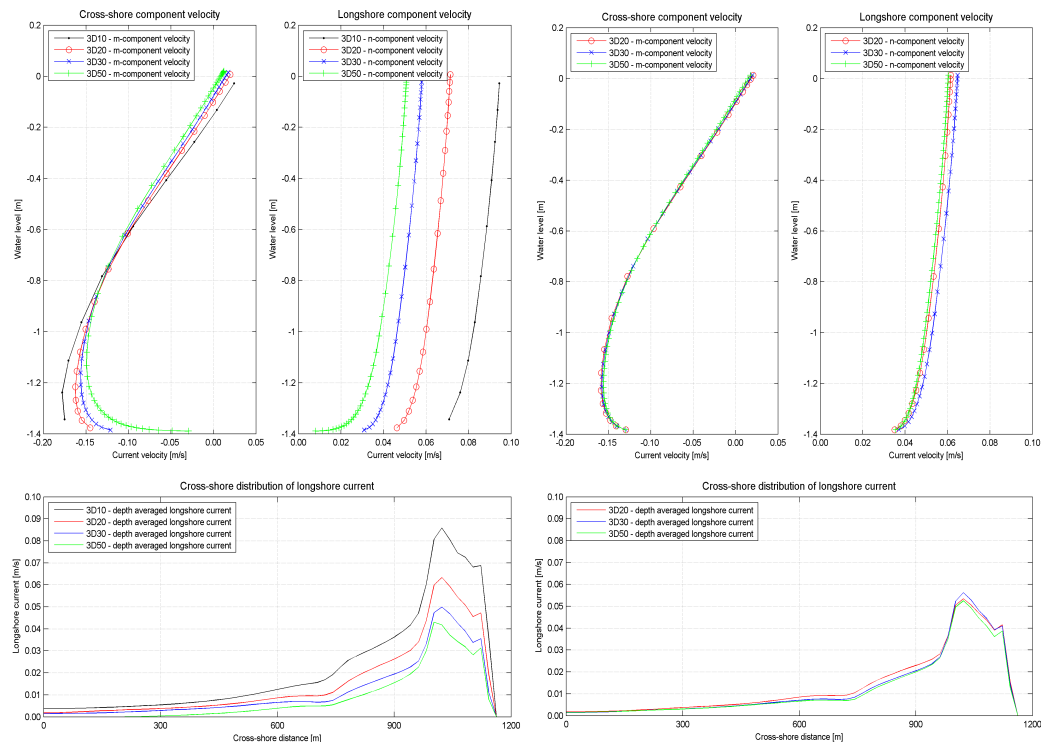


Figure 4.13 Vertical distribution of V_c and V_L velocity for wave condition 1 at a wave angle of 5 degrees. Left figure for a varying thickness of the boundary layers, right figure for a equal thickness of the boundary layer

Table 4.4 Maximum depth-averaged velocity for $H_s = 1\text{m}$ and $T_s = 5\text{s}$

Simulations	#-layers	Delft3D		
		V_c (m/s)	V_L (m/s)	Bottom layer *
2DH (ref.)	1	- 0.11	0.14	100 %
3D10	10	- 0.10	0.09	6.7 %
3D20	20	- 0.10	0.06	1.9 %
3D30	30	- 0.10	0.05	0.7 %
3D50	50	- 0.10	0.04	0.1 %

* As percentage of the total water depth

Table 4.5 Maximum depth-averaged velocity for $H_s = 1\text{m}$, $T_s = 5\text{s}$ – same thickness of bottom layer

Simulations	Delft3D			
	#-layers	V_c (m/s)	V_L (m/s)	Bottom layer *
2DH (as ref.)	1	- 0.11	0.14	100 %
3D20	20	- 0.10	0.05	1 %
3D30	30	- 0.10	0.06	1 %
3D50	50	- 0.10	0.05	1 %

* As percentage of the total water depth

This implies that the vertical distribution of the longshore is largely dependent on the thickness of the layer just above the bed. Note: a 10 layer vertical distribution with a layer thickness of 1 % at the bottom layer would require a large variation factor. The variation factor determines the differences in thickness of subsequent layers. A large variation factor can induce numerical errors and therefore a 10 layer vertical distribution is not included (see Table 4.4).

The bed shear stress is determined following the quadratic friction law. In the 3D approach the bed shear stress is determined using the velocity in the layer just above the bed and the assumption of a vertical logarithmic distribution of the current velocity (as described in paragraph 3.2.6). However, due to wave action the vertical distribution of the longshore current might deviate from the standard logarithmic velocity distribution. This is mentioned in literature (Visser, 1991). Therefore it is interesting to see whether the vertical velocity profile shows the same changes for current induced by a gradient in the water level for which the assumption of a logarithmic velocity profile is valid. This is described in paragraph 4.4.

4.4 Gradient induced current

4.4.1 Introduction

In Delft3D a different routine is used to compute the bed shear stress for the situation with currents only and for combined currents and waves due to the non-linear wave-current interaction (Fredsøe, 1984). Therefore it is interesting to see whether calculations excluding waves will show the same dependency between the vertical distribution of the longshore current and its magnitude and the thickness of the computational layer just above the bed.

4.4.2 Model set up

A model is used to determine the vertical distribution of the current velocity in a situation without waves. The model is 6 grid cells (x-direction) wide and 45 grid cells long (y-direction). The width and length of a single grid cell is respectively 20 and 40 meters. This results in a width and length of the modelled area of 120 meters by 1800 meters. Furthermore, a uniform depth is assumed of 5 meters. The model consists of two open boundaries and two closed boundaries. Between both open boundaries there is a water level difference of 0.1 meter. According to the Chézy formula, the gradient in the water level results in a current velocity of approximately 1 m/s. The Chézy formula reads:

$$v = C\sqrt{Ri} \quad (4.1)$$

In which,

R Hydraulic radius [m]
 i Slope in water level [m/m]

This gradient will lead to a current velocity of approximately 1 m/s. The value of 1 m/s is chosen arbitrarily. Waves are excluded in this model so only the Flow-module is used.

4.4.3 Model results

The computed vertical distribution of the current velocity induced by a gradient in the water level of the different vertical layer distributions are in correspondent well with each other (see Figure 4.14 and Table 4.6). The differences between the vertical distributions for a different number of vertical layers found for wave-induced currents (Figure 4.13) are not found for gradient induced currents. Both figures show the velocity computed for different number of vertical layers (10-50) and the left figure shows the vertical distribution of the current for a varying thickness of the layer just above the bottom. The right figure shows a constant thickness of the layer just above the bed. A different thickness of the layer just above the bed has influence on the vertical distribution of the longshore current. However, these changes are relative small and compared with the differences found in paragraph 4.3.5, where the differences between 2DH and 3D computed values differed up to a factor 2, negligible. Consequently, it could be argued that the different layer distributions only affect the computed currents if the waves are included. The reason for this is that the bed shear stress is determined based on the assumption of a logarithmic vertical velocity distribution. However, wave-breaking induced enhancement of turbulent kinetic energy tends to smooth the vertical distribution of the velocity. Therefore the assumption of a logarithmic vertical distribution of the current velocity is not being valid anymore.

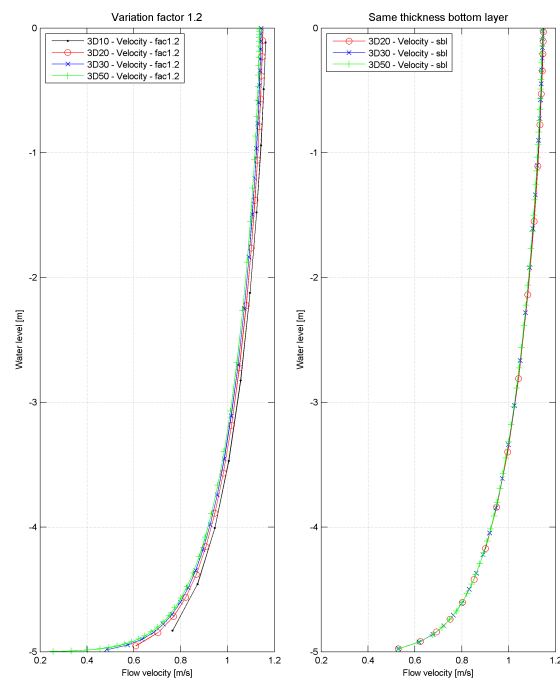


Figure 4.14 Vertical distribution of the V_L due to a gradient in the water level. Waves are excluded

Table 4.6 Depth averaged current velocity at (M,N) is (4,23) for the left graph in the figure above.

Simulations	Delft3D		
	#-layers	V_L (m/s)	Bottom layer *
3D10	10	1.04	6.7 %
3D20	20	1.02	1.9 %
3D30	30	1.02	0.7 %
3D50	50	1.01	0.1 %

* As percentage of the total water depth

4.4.4 Conclusion gradient-induced current

If waves are excluded but a flow exists which is generated due to a gradient in water level there seems to be no dependency between the number of vertical layers of the computed current. Delft3D computes the bed shear stress assuming a logarithmic vertical distribution of the longshore current. As waves enhance vertical mixing the assumption of a vertical logarithmic distribution is not valid anymore. In the case of this additional research the assumption of a logarithmic vertical distribution of the currents is valid and therefore the computation of the bed shear stress is valid also.

4.5 Resolving layer dependency

4.5.1 Introduction

As described in the previous paragraphs large differences are found between 2DH and 3D computations of wave-driven currents inside the surf zone. The discrepancy increases as the number of vertical layers increases and more specific as the thickness of the layer just above the bed decreases. This paragraph briefly describes the cause of this difference. For a more detailed description see Van der Werf (2008).

4.5.2 Solving layer dependency

Formula (4.2) explains the dependency on the thickness of the layer just above the bed.

$$C_{3D} = \frac{\sqrt{g}}{\kappa} \ln \left(1 + \frac{\Delta z_b}{2z_0} \right) \quad (4.2)$$

If Δz_b reduces, also C_{3D} reduces, increasing the roughness. If the assumption of a logarithmic velocity profile is valid, increasing the roughness is justified as a lower velocity at the bottom needs a higher roughness to obtain the same value for the bed shear stress. However, if the velocity profile deviates from the standard logarithmic profile and is more uniform, due to for instance wave action, than a higher roughness (lower value of C_{3D}) as Δz_b reduces is not justified since u_b does not decrease according to the assumption of a vertical logarithmic velocity profile. Therefore, according to equation (3.16) the bed shear stress is overestimated which results in unrealistic low values of the longshore current.

To solve the dependency on the thickness of the first computational layer, this thickness needs to be excluded in the computation of the roughness coefficient. The logarithmic velocity distribution is assumed for the distance between the middle point of the layer just above the bed and the bed itself. Since this distance is often very small and to obtain the friction velocity a certain assumption of the velocity distribution to the bed is needed, this assumption can be justified. To cope with the layer dependency the bed shear stress should be computed using a fixed location in the vertical from which the distance between that point and the bottom is independent of the thickness of the layer just above the bed. This implies that the location in the vertical at which the bed shear stress is determined is no longer dependent on the thickness of the layer just above the bottom, thus solving the dependency on the layer thickness. From this fixed location in the vertical still a logarithmic velocity distribution towards the bottom is assumed which is, as stated before, valid.

Figure 4.15 shows the effect of computing the bed shear stress using the velocity at the edge of the wave boundary layer for the maximum wave-induced longshore current. The selected significant wave height is 1 m and the corresponding wave period is 5 s. The results for the different vertical

layer distributions are in good correspondence with each other. The computed longshore velocities are higher than the velocities shown in Figure 4.13, which concerns the same wave condition and location.

4.5.3 Conclusion

Although there are still differences between the computations, these differences are small and converge (the differences between 30 layers and 50 layers are negligible).

This new approach of computing the bed shear stress, by using the velocity at a fixed location in the vertical resolves the dependency of the computations of the wave-driven longshore currents inside the surf zone. In the following chapters this new approach is validated against both laboratory and field measurements.

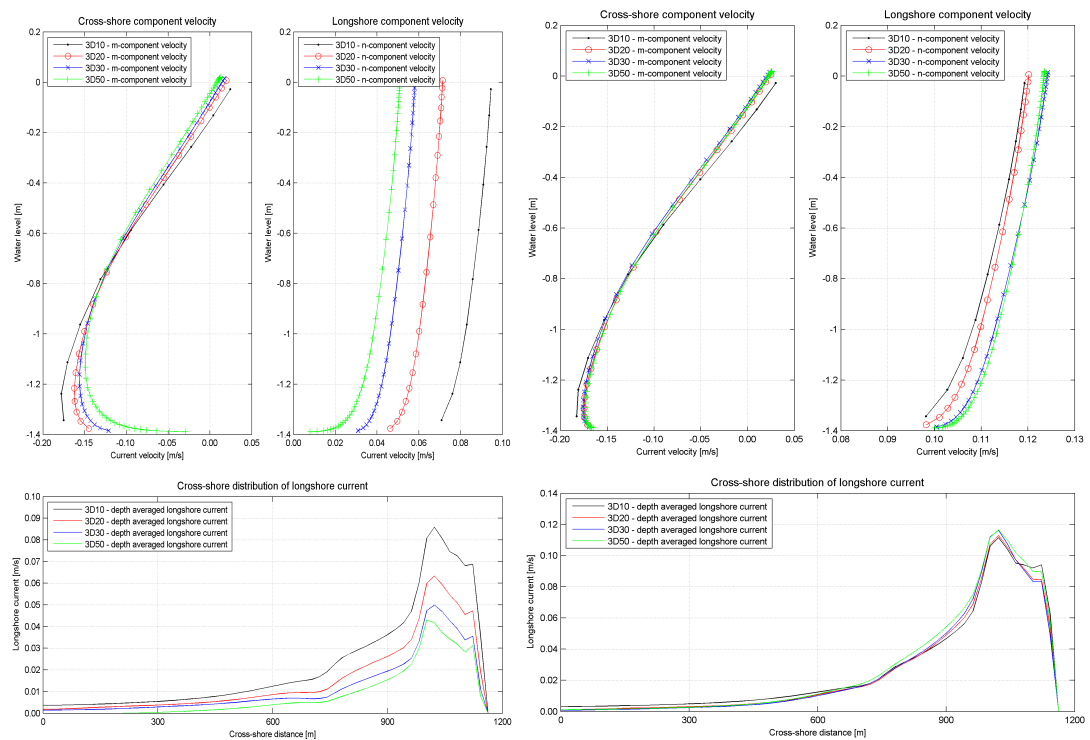


Figure 4.15 Vertical distribution of V_c and V_L for the new approach (right figure) compared with the old approach (left figure) of computing the bed shear stress

Table 4.7 Depth averaged current velocity for new approach bed shear stress

Runs	#-layers	Delft3D	
		V_L (m/s)	Bottom layer
2DH	1	0.14	100 %
3D10	10	0.11	6.7 %
3D20	20	0.11	1.9 %
3D30	30	0.12	0.7 %
3D50	50	0.12	0.1 %

4.6 Conclusion

The 3D approach differ from the 2DH approach by including one extra dimension in the momentum equation and including wave-breaking enhanced vertical mixing, streaming and Stokes drift aiming at computing a realistic vertical distribution of the current velocity. However, it is shown that the 3D computations differ unrealistically from the 2DH computations for wave-driven longshore currents inside the surf zone. Increasing the number of vertical layers results in an increasing discrepancy between the 3D and 2DH computations of the longshore current. The cause for this is the method that is used to determine the bed shear stress. The bed shear stress is computed using the quadratic friction law and the assumption of a logarithmic velocity distribution. If the assumption of a logarithmic velocity distribution is valid (e.g. water level gradient induced flow) the computations show little dependency on the number of vertical layers. However, in the presence of wave-breaking the vertical distribution deviates from a logarithmic profile. Computing the bed shear stress using a point in the vertical which is independent on the thickness of the layer just above the bed significantly reduces the dependency of the computed longshore current on the number of vertical layers.

This new method of computing the bed shear stress is validated in the following paragraphs for the laboratory tests performed by Reniers and Battjes (1997) and field measurements obtained at Sandy Duck, North Carolina, USA in 1997.

5 Validation laboratory experiments Reniers and Battjes

Results

- *New method of computing the bed shear stress improves the 3D computations compared with measurements*
- *Important calibration parameters are found to be the background horizontal eddy viscosity, the bottom roughness and the value of the roller slope (β_{roller})*
- *After calibration; both the results from the 2DH and 3D approach correspond well with measurements. However, the wave-driven currents in the bar trough are underestimated by both the 2DH as the 3D approach*
- *Increasing the number of vertical layers does not increase the accuracy of the computations. However, it is found that using 5 layers some inconsistencies in the bar trough occurs*
- *Compared with the computations by Reniers and Battjes; the seaward predictions of the longshore current is improved. The underestimation of the wave-driven current in the bar trough is still present*
- *A value for γ according Ruessink et al (2003) should be the default setting in Delft3D*
- *It is argued that the effect of the roller induced mass-flux is small*
- *Including wave forcing results in a deviating cross-shore distribution of the longshore currents compared with measurements. However, it is argued that including the wave forces is physically more realistic*

5.1 Introduction

The goal of this Chapter is:

- to validate the new method of computing the bed shear stress, i.e. using the velocity in the layer above the wave boundary layer
- to validate 2DH and 3D computed results with measured data

Since the layer dependency of the 3D computations occurred only inside the surf zone in the presence of waves it is interesting to validate the modelled results using measurements of wave-induced currents inside the surf zone isolating as many processes as possible. Therefore a comparison with laboratory obtained results is preferable. Processes as wind, tide and a changing bathymetry are avoided. Furthermore, an irregular bathymetry, which can cause alongshore variations in the currents are also avoided. Reniers and Battjes (1997) performed laboratory measurements of random waves approaching a barred beach.

In the following paragraphs the laboratory test of Reniers and Battjes are discussed and the tests with random waves are simulated using Delft3D. The effect of computing the bed shear stress based on the velocity at the edge of the wave boundary layer is reviewed. In paragraph 5.2 the laboratory tests by Reniers and Battjes are discussed. The laboratory set up, the used theory by Reniers and Battjes to reproduce the measured data and the results are described. In paragraph 5.3 the model set up in Delft3D is discussed and the first results using the new approach for the bed shear stress is described in paragraph 5.4. In paragraph 5.5 the first results are calibrated to obtain accurate results compared with the measurements. In paragraph 5.6 a model sensitivity analysis is performed to understand the influence of certain parameters to the computed longshore current. Paragraph 5.7 describes the final results and discusses the model successes and insufficiencies. The conclusions of the validation using laboratory experiments are mentioned in paragraph 5.8.

5.2 Laboratory experiments Reniers and Battjes (1997)

5.2.1 Set up laboratory experiment

The purpose of the laboratory experiments performed by Reniers and Battjes was to investigate the cross-shore distribution of the wave-driven longshore currents in general and in specific whether the location (in the cross-shore) of the maximum wave-driven longshore current is in the trough or the crest of the breaker bar.

Reniers and Battjes performed the measurements on a barred concrete slope in a large wave basin (25 m x 40) as shown in Figure 5.1. A pump system was used to re-circulate the wave-driven longshore current creating an alongshore uniform current and preventing strong offshore directed flow along the wave guide. The beach was rotated with respect to the wave maker to gain beach length. Furthermore, wave guides were applied to prevent the waves from diffracting avoiding alongshore variation of wave-set up. The cross-shore distribution of the longshore current was measured using electromagnetic flow meters (EMF) located at one-third of the depth which is roughly equal to the depth averaged velocity when assuming a logarithmic velocity profile ($z=h/e \sim 0.37h$). The measured current velocity data showed errors in the order of 1 cm/s.

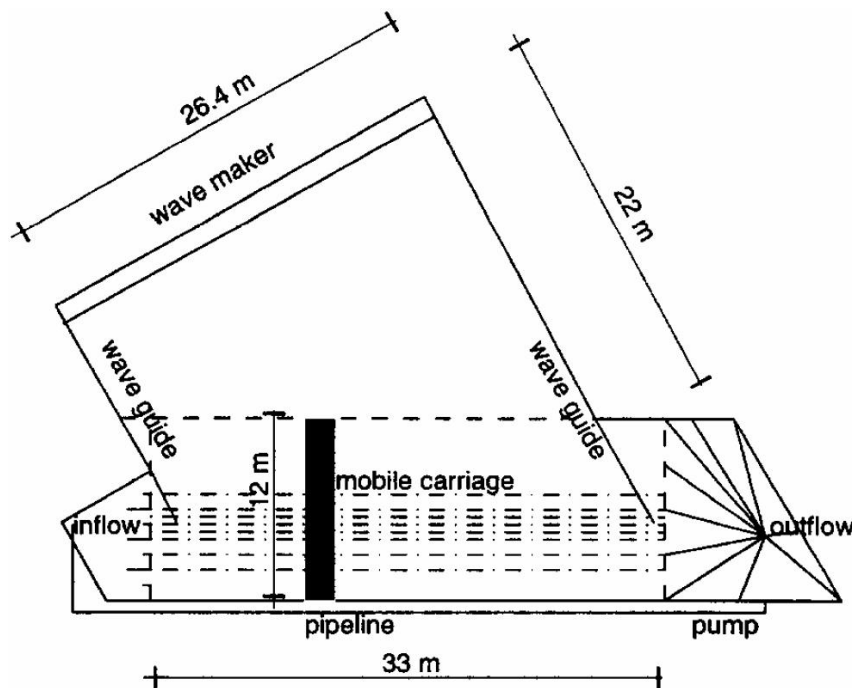


Figure 5.1 Basin layout; the dash-dotted lines indicate the position of the bar (Reniers and Battjes, 1997)

The test conditions by Reniers and Battjes used in this study concerns random waves with a significant wave height (H_s) of 0.1 m, a wave period (T_p) of 1.2 s and a wave angle (θ_w) of 30° .

5.2.2 Results by Reniers and Battjes

Reniers computed the cross-shore distribution of the wave-induced longshore currents from the wave-averaged and depth-integrated longshore momentum equation. The forcing is obtained from the linear wave theory including the roller contribution as given by Deigaard (1993) which is similar as described in Appendix B. Reniers and Battjes found that the cross-shore distribution of the longshore current velocity profile matches the measured distribution quite well (Figure 5.2). In particular the location of the maximum longshore current coincides well with measurements. However, Reniers and Battjes observed that the longshore current velocities were overestimated at the seaward end of the bar and underestimated in the trough. Reniers and Battjes argued that the causes of these differences

are difficult to determine since the forcing, mixing and bottom friction have similar order effects on the predicted current velocities in these areas.

Furthermore, Reniers and Battjes discussed the effect of the roller contribution and the horizontal mixing and concluded that both processes are important to obtain a reasonable agreement between computed and measured velocities. Although both processes influence the longshore current profile with a comparable magnitude, the effect is of a different kind, i.e. the roller shifts the profile shoreward while mixing spreads the profile. Reniers and Battjes concluded that the maximum longshore current at barred beaches occurs at the crest of the breaker bar.

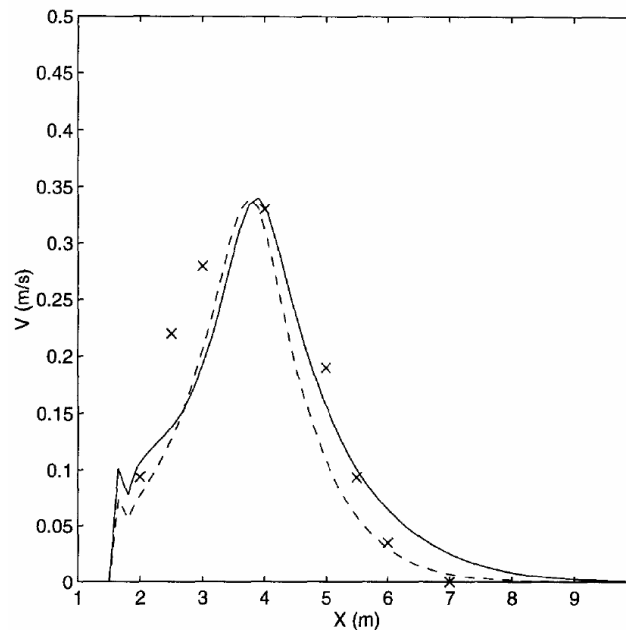


Figure 5.2 Computed longshore currents by Reniers and Battjes. Dashed line indicates linear roughness and solid line non-linear bottom shear stress. Data compared with measurements.

The laboratory experiments of Reniers and Battjes provides the opportunity to validate the 2DH and 3D approaches in Delft3D and to compare the 2DH and 3D computed results with each other. The results computed by Reniers and Battjes also offer the opportunity to compare computed longshore current velocity distributions, using the velocity in the layer just above the edge of the wave boundary layer to determine the bed shear stress, and check whether the same over- and underestimations are found.

5.3 Delft3D set up

In contrast to field situations, the laboratory set up justifies the assumption of an alongshore uniform longshore current. Therefore such a problem could be simplified using 2DV (i.e. profile model with vertical layers) computations (Johnson and Smith, 2005; Ruessink et al., 2003). However, to make a comparison between 2DH and 3D computation the problem is approached using three-dimensional computations.

The wave grid is constructed much larger than the flow grid to get a uniform wave field in the area of interest. The flow-grid consists of 101×5 grid points and has 15 vertical layers with a thickness of the layer just above the bed of 1.7 % of the water depth. Figure 5.3 shows a cross-shore profile of the laboratory experiment. Neumann boundary conditions are used for the lateral boundaries which are perpendicular to the coast and a fixed water level boundary condition is used for the open boundary

at the sea side. For the wave module the boundary conditions are the test condition of Reniers for random waves. The significant wave height and wave period are respectively 0.1 m and 1.2 s. The angle of incidence is 30° normal to the coast. Table 5.1 shows the settings applied in the simulations.

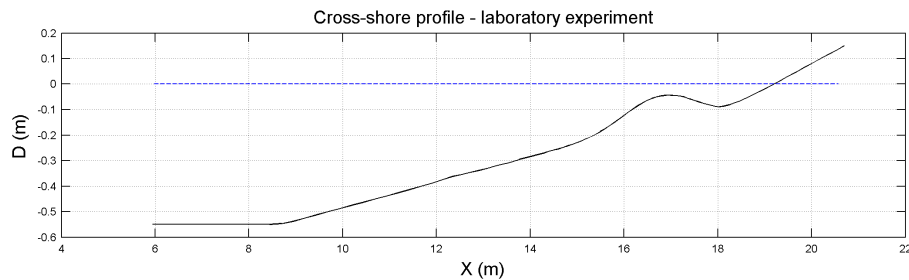


Figure 5.3 Flow bathymetry and grid of Reniers laboratory tests

Table 5.1 Delft3D parameters settings of Reniers laboratory tests

Parameters	Delft3D Settings	
	Default Settings	Used Settings
Simulation time (min)	-	20
Time step (min)	-	0.005
Number of vertical layers (-)	1	15
Reflection parameter alpha (s^{-2})	0	100
Roughness – White Colebrook (m)	-	$5e-4$
Roughness – Chézy ($m^{0.5}/s$)	65	50 / 55 / 60
Background horizontal visc. (m^2/s)	1	1 / 0.02 / 0.005 / 0
Threshold depth (m)	0.1	0.01
Smoothing time (min)	60	60
Roller	no	yes
Cstbnd	no	yes
Gamdiss	0.55	-1
F _{lam} (breaker delay)	0	0 / -1 / -2
FwFac (streaming parameter)	1	0 / 0.1 / 0.5 / 1
β_{roller} (angle of the roller)	0.1	0.01 – 0.1

This model is first calibrated to obtain the best fit with measurements. After this a model sensitivity analysis is made to determine how parameters and process influence the longshore currents. The following calibration parameters are used:

- Background horizontal eddy viscosity
- Bottom roughness
- Streaming
- Angle of the roller (β_{roller})
- Horizontal viscosity based on H_{rms}

The background horizontal eddy viscosity increases the horizontal exchange of momentum. Since the grid size in this model is very small to include the breaker bar, $O(10\text{ cm})$, the default value of the horizontal viscosity in Delft3D ($1\text{ m}^2/s$) is probably too large.

Reniers and Battjes estimated the equivalent geometrical roughness of Nikuradse of the smooth concrete bottom at $k_s = 0.0005\text{ m}$. This can be used as input in Delft3D in the White-Colebrook formulation to determine the Chézy roughness coefficient. This roughness parameter results in a depth-dependent Chézy-coefficient according to:

$$C = 18 \log \left(\frac{12H}{k_s} \right) \quad (5.1)$$

In which H is the total water depth. Besides the estimated roughness by Reniers and Battjes also a depth independent (fixed) Chézy-coefficient will be used to compare to the roughness estimated by Reniers and Battjes. A depth dependent Chézy-coefficient, by equation (5.1), is expected to give a more cross-shore spread flow field since at larger depths the Chézy-coefficient becomes higher, which implies that the bottom becomes less rough, while at small depth the bottom becomes rougher.

Streaming, as mentioned in paragraph 3.2.4, is a wave-induced current in the wave boundary layer which is the result from the fact that the horizontal and vertical orbital velocities are not exactly ninety degrees out of phase. Since streaming is included in 3D and excluded in 2DH computations the effect of it is determined.

Within the roller model the only unknown variable is the roller slope (β_{roller}) as is mentioned in Appendix B. A value of 0.10 is often used and found to provide accurate results (Nairn et al., 1990). However, (Walstra et al., 1996) used inverse modelling techniques to determine the roller slope based on measurements of the wave set up and wave height. The result is a cross-shore varying roller slope. This is also implemented in Delft3D.

For the model sensitivity analysis, the following parameters / processes are varied:

- Turbulence closure model
- Number of vertical layers
- Wave breaking related parameters (γ and α)
- Effect of roller mass-flux
- Radiation stress

These parameters are used in the sensitivity analysis since these parameters are often not taken into account during calibration (e.g. wave breaking related parameters) or are not taken into account at all in Delft3D (e.g. wave forces). To see what the influences are of different choices for these parameters and processes they are examined in the sensitivity analysis.

In Delft3D several vertical turbulence models can be applied. The simplest model is an algebraic turbulence model. The k - L model is a first-order turbulence closure the k - ϵ turbulence model. This is a second-order turbulence closure model which uses a transport equation to determine both the turbulent kinetic energy and the turbulent kinetic dissipation. From the k and the ϵ both the mixing length and the vertical eddy viscosity is determined. The advantage of the k - ϵ model is that the mixing length and vertical eddy viscosity is now dependent on the properties of the flow instead of an algebraic formula. The k - ϵ model is often assumed to be most accurate since it accounts for real processes (e.g. wave-breaking induced enhancement of turbulent kinetic energy).

The number of layers determines the resolution of the vertical distribution of the longshore current. Increasing the number of vertical layers increases the computational time. However, a small number of vertical layers might give an inaccurate vertical distribution of longshore current. Several simulations are made varying the number of vertical layers.

The longshore current is determined based on the amount of roller energy dissipation. The amount of roller energy dissipation is determined by the amount of roller energy which is dependent on the amount of wave energy dissipated. The amount of wave energy dissipation can be calibrated using the breaker parameter (γ), which determines criteria of wave-breaking, and a calibration parameter (α)

which can be used to enhance the amount of wave energy dissipation. These parameters are varied to see if they improve wave height predictions.

In Delft3D the longshore current is, in case of a stationary computation, determined based on the roller force which is induced by the dissipation of roller energy, according to equation (B1.10). The radiation stress induced forces are not taken into account. By neglecting the radiation stress induced forcing the water level set down, which is determined by the cross-shore differences in the S_{xx} part of the radiation stress, is also not computed. The effect of including the radiation stress induced force is determined.

As wave energy is converted into a roller, also water inside the wave is transferred to the roller. This additional mass-flux is not taken into account in Delft3D and therefore the effect of the roller induced mass-flux is discussed.

Before the results are calibrated a simulation is made comparing the 2DH, 3D and the 3D model using the new approach for computing the bed shear against the measurements to see if this approach is valid. This is described in the next paragraph.

5.4 Result of bed shear stress formulations

In this paragraph the adjusted 3D model is compared with the 2DH and the original 3D model. This is to compare and validate the new method of computing the bed shear stress with the original method, with the 2DH approach and with measurements.

The first results with the default settings of Delft3D are shown in Figure 5.4 for the 2DH, the adjusted 3D and the original 3D computations. Note; these results are not yet calibrated. The first results show that the wave height is predicted reasonably well (top-left figure of Figure 5.4). However, the amount of wave energy dissipation is too low compared with measurements (for all simulations). Therefore, the wave height in the bar trough is overestimated. The water level is also quite well represented by the computations for all different runs. Wave-induced water level set down is not taken into account since the wave-induced radiation stresses are not applied; only the forces by the roller are taken into account (Appendix B.3). Since the roller model only induces a force if wave energy is dissipated, the set down (wave breaking does not occur yet) is not included. Furthermore, this figure shows clearly the effect that computing the bed shear stress based on the velocity at the edge of the wave boundary layer has on the depth-averaged longshore current. The original 3D model significantly underestimates the longshore current while the improved model shows better agreement with the measurements. Both 2DH and the improved 3D (especially) overestimates the longshore current seaward of the breaker bar while underestimating the longshore current in the bar trough. Also both 2DH and 3D show an overestimation of the computed wave height in the bar trough. In the next paragraph the improved 3D model is calibrated to give more accurate results.

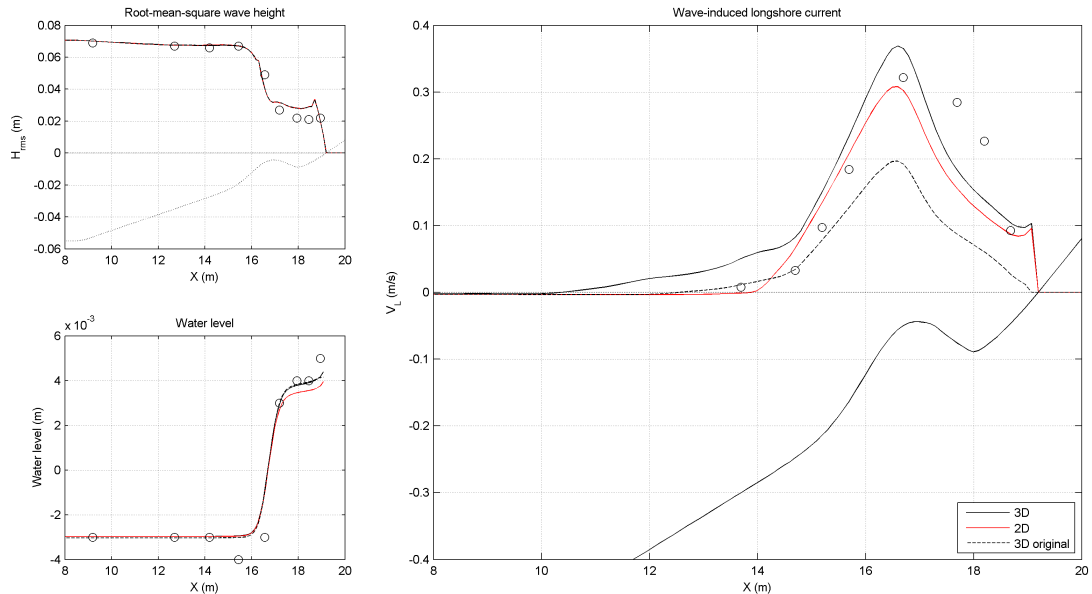


Figure 5.4 Root-mean-square wave height (top left figure), water level (bottom left figure) and depth averaged longshore current (right figure) for 2D, 3D original and 3D computations

5.5 Calibration

As mentioned in paragraph 5.2 several parameters are used for the calibration of the Delft3D model. Since only one dataset with 8 measuring locations in the cross-shore direction is available, of a test with random waves, the statistical reliability is not determined (i.e. root-mean-square error or r^2). Just one deviation already has significant influence on the statistical reliability and therefore the results might be biased upon a single deviation.

The goal of the calibration is to achieve computations which are in good agreement with the measurements by adjusting the parameters within physically realistic boundaries. Furthermore, also the goal is to understand which parameters in Delft3D are important for tuning the computations of the longshore currents.

5.5.1 Background horizontal eddy viscosity

Figure 5.5 shows the computed results for different values of the horizontal viscosity compared with the measurements. The top left figure shows the computed wave height as H_{rms} , the bottom left figure shows the water level set up and the right figure shows the longshore current. The computed values are compared with the measured values, which are the circles and the dots. The error bar in the right figure shows the uncertainty of the measurement. The default value of $1 \text{ m}^2/\text{s}$ (black-line), of the horizontal background eddy viscosity gives an unrealistic uniform distribution of the depth averaged longshore current while the external forcing, i.e. wave height and water level, show good agreement with the measurements. This is due to the high exchange rate of horizontal momentum due to the relative high background eddy viscosity. If the background horizontal eddy viscosity decreases again the external forcing remains in good agreement but now also the profile of the computed depth averaged longshore current becomes more realistic. Excluding the background eddy viscosity approximates the measurements closest. In this case only the wave-breaking induced horizontal viscosity is added by the roller model to the system.

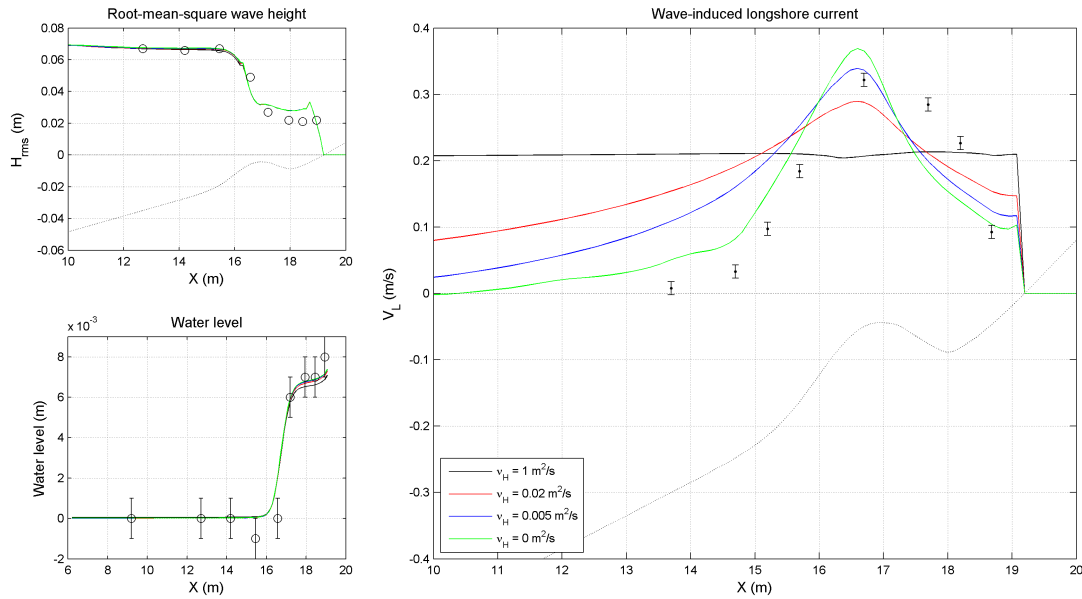


Figure 5.5 Computed values of H_{rms} , the water level and the longshore current compared with measurements for different values of the horizontal background eddy viscosity

Furthermore, the right figure inside Figure 5.5 shows that for a decreasing horizontal eddy viscosity, thus reducing the horizontal mixing, the location of the longshore currents is not influenced. This is because the forcing remains the same. Reducing the horizontal eddy viscosity does influence the magnitude of the maximum longshore current. This can be explained by the fact that a larger horizontal eddy viscosity increases the amount of momentum transferred horizontally. This reduces the maximum longshore current but increasing the magnitude nearshore and seaward resulting in a more uniform distributed longshore current.

Since a value of $0 \text{ m}^2/\text{s}$ for the background horizontal eddy viscosity shows the best agreement with measurements, this setting is used for the further calibration.

5.5.2 Bottom roughness

The bottom roughness as estimated by Reniers and Battjes ($k_s = 0.0005 \text{ m}$) results in a depth-dependent Chézy-coefficient according to (5.1). This implies that if the depth increases, the Chézy-coefficient increases accordingly, thus reducing the bottom roughness. Delft3D overestimated the longshore current seaward of the breaker bar. A fixed Chézy roughness coefficient might reduce this overestimation. The equivalent geometrical roughness of Nikuradse is compared with fixed Chézy-coefficients in Figure 5.6. The left figures show that a different roughness formulation and value has little effect on the wave height while it does influence the longshore current. This is due to the fact that the bottom roughness is not included in the roller model and therefore no dissipation of wave energy due to the bottom roughness is taken into account. The longshore current, however, is influenced by the choice of roughness formulation and value.

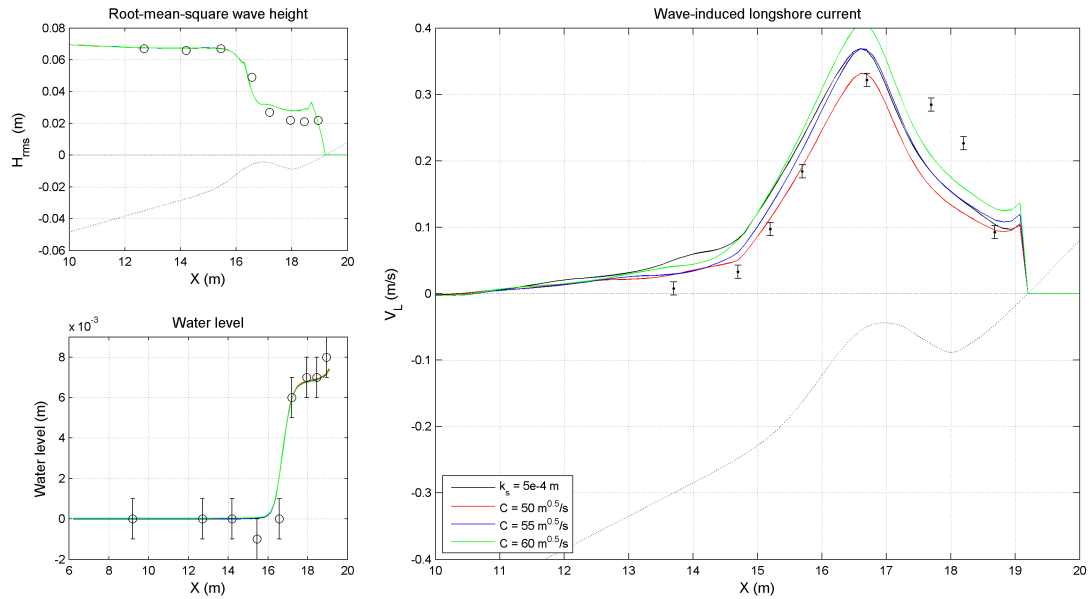


Figure 5.6 Computed values of H_{rms} , the water level and the longshore current compared with measurements for different values of the roughness coefficient

The longshore current is determined by the balance between the cross-shore gradients in the (S_{yx} part of the) radiation stress, which is induced by waves, and the bed shear stress which has to be induced by the longshore current. The bed shear stress is determined by the roughness of the bottom and a current, according to (simplified):

$$\tau_b \sim \frac{u^2}{C^2} \quad (5.2)$$

Where,

τ_b	bed shear stress	[N/m ²]
u	current velocity	[m/s]
C	Chézy roughness coefficient	[m ^{0.5} /s]

If the forcing remains constant then a reduction of the bottom roughness (increasing Chézy) results in an increase of the longshore current to obtain the same bed shear stress to compensate for the cross-shore gradients in the radiation stress. The right figure of Figure 5.6 shows that increasing the Chézy-coefficient, thus reducing the roughness, results in higher velocities and vice versa. The location of the peak velocity does not change since the distribution of the forcing does not change. Since the Nikuradse coefficient is dependent on the water depth, a larger water depth leads to a larger Chézy-coefficient (less rough) the velocity profile is slightly more spread than using a fixed Chézy-coefficient.

Figure 5.6 shows that for a Chézy-coefficient of 50 $m^{0.5}/s$ the depth-averaged longshore current is in good agreement with the measured currents from outside the breaker bar till the location of the maximum longshore current. However, as mentioned in paragraph 4.3.3 the seaward overestimation of the longshore current is probably due to an overestimation of the contribution of streaming. By reducing the influence of streaming a significant reduction of the seaward longshore current is found (see paragraph 5.5.3).

For further calibration the roughness as determined by Reniers and Battjes is used. Paragraph 5.5.3, shows that the seaward longshore current can be reduced by reducing the contribution of streaming.

Furthermore, this value, which is related to a physical roughness element, seems more realistic to use than a fixed Chézy coefficient.

5.5.3 Streaming

Choosing a fixed Chézy roughness coefficient did not significantly affect the overestimation of the longshore current seaward of the breaker bar. As mentioned in paragraph 3.2.4 streaming strongly depends on the wave height. The magnitude of streaming is closely related to the dissipation of wave energy due to bottom friction. The dissipation of wave energy due to bottom friction can be calibrated by varying the calibration parameter for streaming (Fwfac). For this calibration, Fwfac is varied between 0 (excluding streaming) and 1. Figure 5.7 shows the computed results of different values of the friction parameter. Varying Fwfac clearly influences the longshore current at the location where relative high waves occur as is expected since the orbital velocity is related to the root-mean-square wave height. The values of 0 and 0.1 for Fwfac correspond well to the measurements. However, a value of 0 excludes the process of streaming while this process is real, although schematically implemented (as a shear stress), and realistic (Fredsøe and Deigaard, 1992).

Since a value of 0.1 provides the best fit and is more realistic to use this value is used for further calibration.

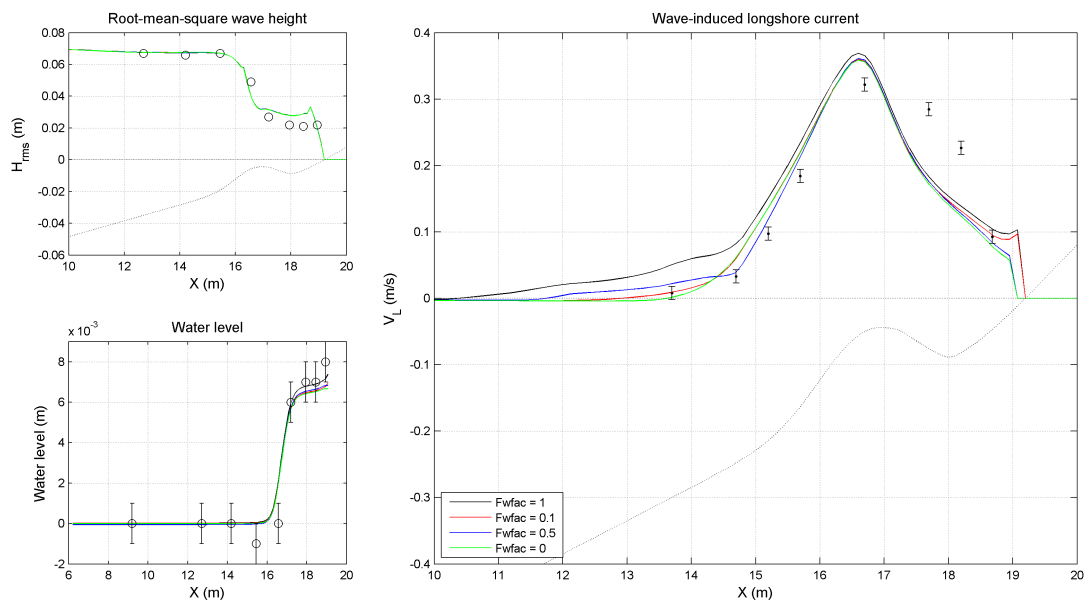


Figure 5.7 Computed values of H_{rms} , the water level and the longshore current compared with measurements for different values for the streaming calibration factor

5.5.4 Angle of the roller

The slope of the roller determines the rate of roller energy dissipation. As wave energy is dissipated due to breaking, the energy is not instantly released but first converted to roller energy which is transported on top of the wave with the same velocity as the wave. The dissipation of roller energy is the driving force of the longshore current in Delft3D (described in Appendix B). During the transportation, the roller energy is dissipated at a rate depending on the slope of the roller, the amount of wave energy and the velocity at which the roller bore transports itself on top of the wave. Increasing the slope of the roller results in an earlier release or dissipation of the roller energy and therefore a higher and more concentrated roller dissipation. This results in a more concentrated

longshore current. Figure 5.8 shows the computed results for different roller slopes. In this figure additional parameters are added to give more insight in the effect of the roller slope.

A gentle slope clearly results in a lower longshore velocity since less roller energy being dissipated (bottom middle figure). The dissipation of roller energy directly causes a force which drives the water and generates the longshore current. Since the dissipation of the roller energy slows down due to a gentle slope, the roller energy is transported further towards the coast (middle figure). In the contrary a steeper slope in the roller results in an almost instant (higher) dissipation of roller energy (bottom middle figure). Furthermore, the bottom left figure of Figure 5.8 shows the wave force which is zero for all computations. This is due to the fact that the wave forces are set at zero in the roller model is included. Therefore the forcing of the current is only due to the roller dissipation induced force.

A roller slope of 0.05 provides the best fit to the measured longshore currents and is therefore used for further calibration.

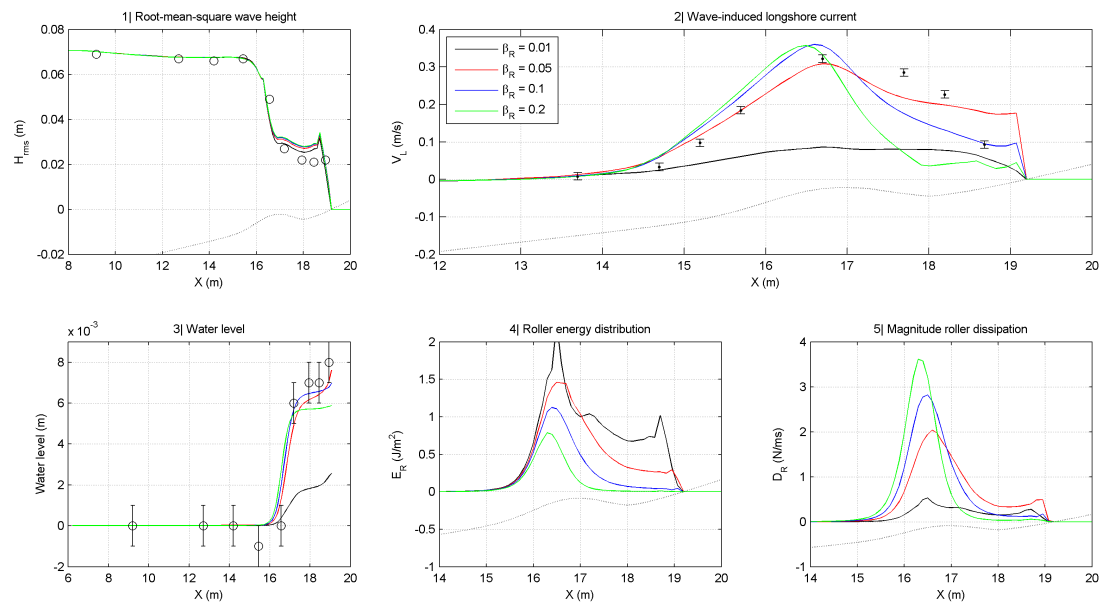


Figure 5.8 Root-mean-square wave height (1), water level (3), depth averaged longshore current (2), roller energy (4) and roller dissipation (5) for different values of the roller slope

5.5.5 Horizontal viscosity

Reniers and Battjes used the H_{rms} as vertical mixing length in the formulation of the horizontal eddy viscosity, according to:

$$\nu_t = H_{rms} \left(\frac{D}{\rho} \right)^{\frac{1}{3}} \quad (5.3)$$

However, in Battjes (1975), Battjes uses the water depth (h) as the vertical mixing length scale instead of the root-mean-squared wave height. Delft3D also applies the water depth as vertical mixing length to determine the horizontal eddy viscosity. To determine the differences Delft3D is adjusted to compute the horizontal viscosity using the H_{rms} as vertical length scale. To determine if this approach influences the performance of the computations by Delft3D a simulation is made using the root-mean-square wave height as vertical length scale. Figure 5.9 shows the results. The computed longshore current is less spread for using the H_{rms} (red-line) as mixing length-scale. As waves break a

sharp reduction in wave height is found. This implies that the viscosity becomes smaller in the bar trough than if the water depth is used since in the trough the water depth increases (see bottom left figure). Seaward both approaches show similar results. Using the H_{rms} as the vertical mixing length for the horizontal turbulence leads to a contrary effects inside the bar trough. Since the depth is used as the vertical mixing length in the bar trough, where the depth increases, the amount of horizontal mixing increases. Therefore more momentum is transferred from the location of the maximum longshore current towards the bar trough. For further simulations the depth is used as vertical mixing length.

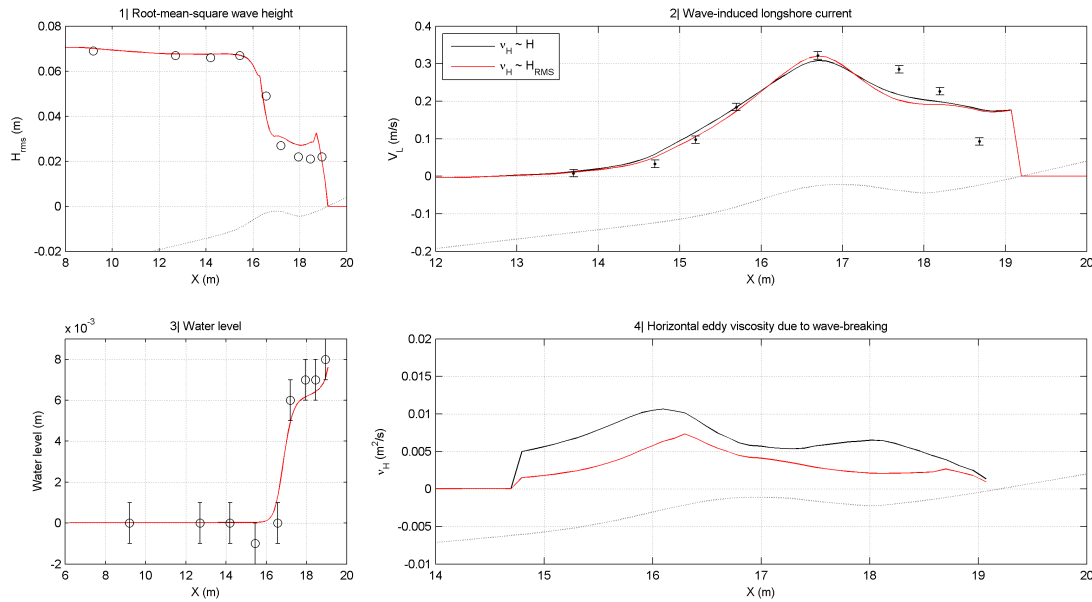


Figure 5.9 Wave height (1), water level (3), depth-averaged longshore current (2), horizontal eddy viscosity (4) for the different approaches for the wave-induced production of horizontal eddy viscosity

5.6 Model analysis

In Delft3D different parameters can be varied, which all affect the computation of the wave-induced longshore current. For instance, the type of vertical turbulence closure model and the breaker parameter. In this paragraph some simulations are made varying some Delft3D settings to gain more insight in the sensitivity of the computed currents by these choices. The effect of choosing a different vertical turbulence model, a different number of vertical layers and a different breaker parameter (γ) is analysed. Furthermore, the possible effect of including the roller mass-flux induced current is discussed and the effect of computing the longshore current using both the wave forces and the roller forces is described.

5.6.1 Vertical turbulence model

Within Delft3D different closure models can be used to calculate turbulence. The choice of a turbulence closure model influences the longshore current calculations. In this paragraph the effects of different turbulence closure models is looked at. Figure 5.10 shows the simulated results for three different turbulence closure models using the Delft3D settings as described in the previous paragraph. The choice of turbulence closure model considerably influences the computed longshore current. All different turbulence models compute the longshore current quite good up to the location of the maximum longshore current at the bar crest. The $k-L$ model predicts the location of the maximum longshore current further shoreward and higher compared to the other models and the

measurements. However, the k - L model seems to compute the longshore currents inside the bar trough better but very close to the shore it overestimates the longshore current.

Since the k - ϵ turbulence model relates the vertical mixing length and the vertical eddy viscosity to actual flow properties this model is assumed to give more realistic distribution of the velocity.

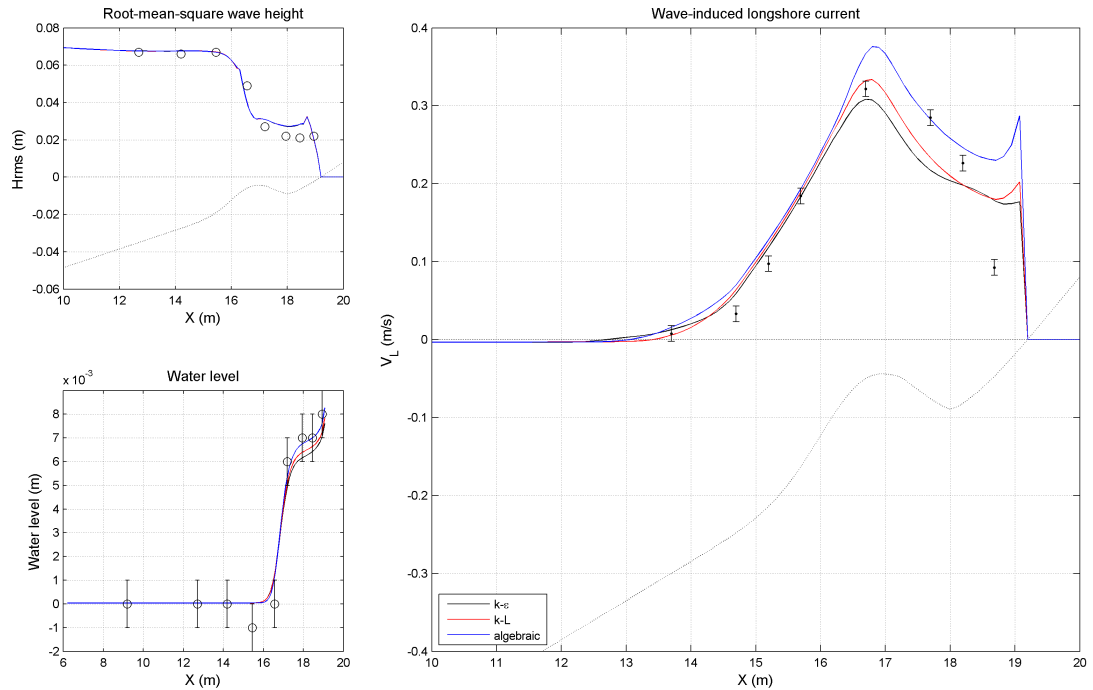


Figure 5.10 Root-mean-square wave height (top left figure), water level (bottom left figure) and depth averaged longshore current (right figure) for different 3D turbulence models

Figure 5.11 shows the vertical distribution of the longshore current at the location of the measurements for the different turbulence closure models. The measurements are located at one-third of the water depth from the bottom. The vertical distribution of the longshore current significantly changes at some locations for the different turbulence closure models. Since only one measurement over the vertical is made, little can be said over the performance of Delft3D in computing the vertical distribution of the longshore current.

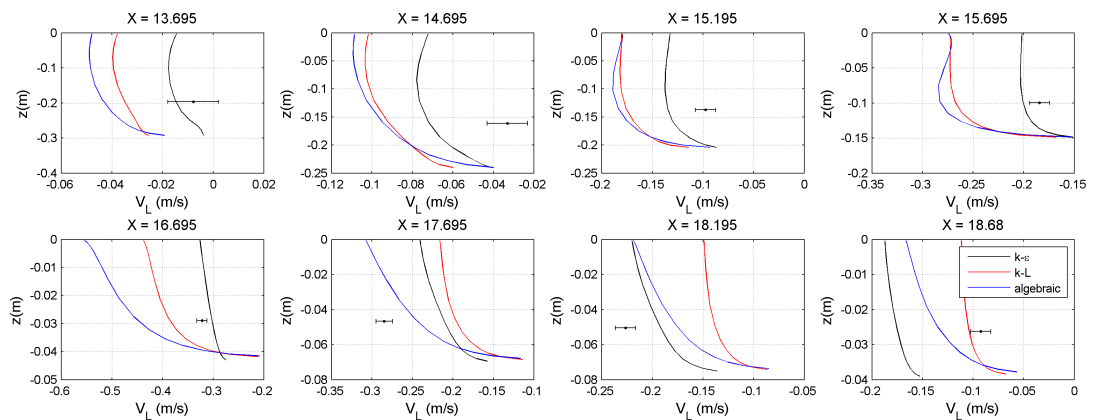


Figure 5.11 Vertical distribution of the longshore current for three different turbulence closure models. The dot denotes the measured longshore current

5.6.2 Vertical computational layers

The effect of varying the number of vertical layers on the performance of computing the wave-induced currents by Delft3D is determined. Increasing the number of vertical layers provides a more detailed vertical distribution of the current velocity. However, it also results in an increase in computational time. The number of vertical layers is varied between 5, 15 and 30. The layers have the same variation factor between the thicknesses of subsequent layers. Figure 5.12 shows the results for the different amount of vertical layers. There are little differences between the computed wave height, water level set up and longshore currents. However, for 5 vertical layers the longshore current in the trough shows inconsistencies compared with results obtained using 15 and 30 vertical layers.

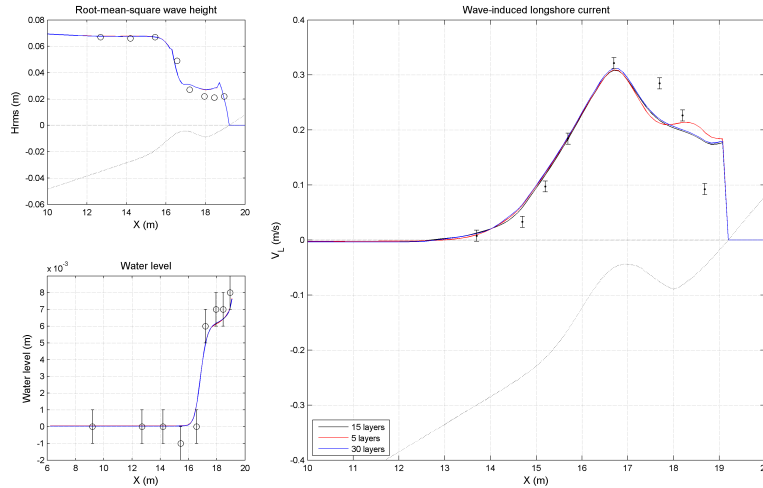


Figure 5.12 Computed values of H_{rms} , the water level and the longshore current compared with measurements for different values for different numbers of vertical layers

The number of layers chosen also influences the vertical distribution of the longshore current. This is shown in Figure 5.13 for 15 layers (black-line), 5 layers (red-line) and 30 layers (blue-line). Increasing the number of vertical computational layers results in negligible changes in the longshore current. However, for the measurements near the shore ($x > 17$) the differences increases (as also is seen in Figure 5.12). Increasing the number results in a more smooth distribution line due to the increased resolution. Based on Figure 5.12 and Figure 5.13 it is not recommended to use a number of 5 layers and concluded that the dependency on the distribution of the vertical layers is solved.

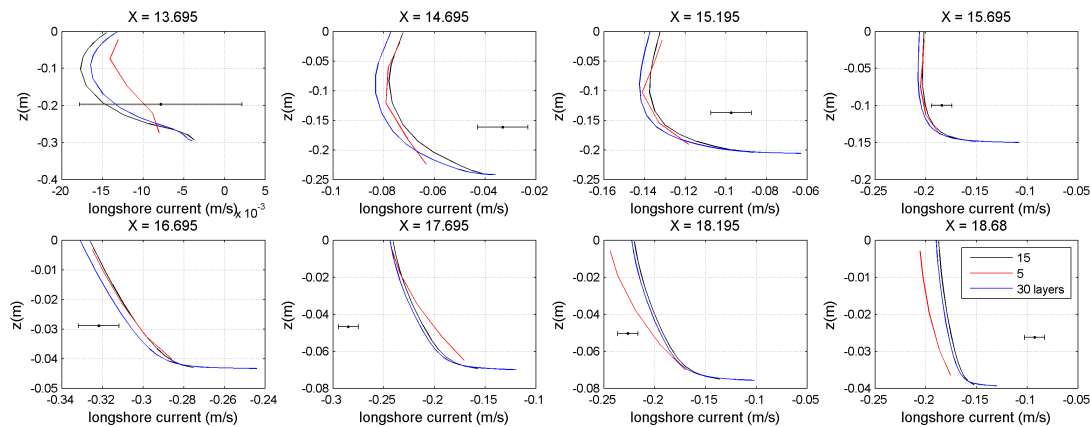


Figure 5.13 Vertical distribution of the longshore current for different number of vertical layers

5.6.3 Wave breaking

The wave height is overestimated inside the bar trough which might cause the underestimation of the longshore current inside the trough. The dissipation due to wave-breaking is computed in Delft3D according to the expression derived by Roelvink (1993) for situations of propagating wave groups in which the wave energy varies slowly;

$$D_w = 2\alpha f_m \left(1 - \exp \left(- \left(\frac{\sqrt{8E/(\rho g)}}{\gamma h} \right)^n \right) \right) E \quad (5.4)$$

In which,

α	calibration parameter	[-]
γ	breaker parameter	[-]
n	calibration parameter	[-]

The breaker parameter and the calibration parameter α can be varied within Delft3D. The sensitivity of Delft3D to different values for these parameters, and if these different values might increase the accuracy of the wave height inside the breaker trough, is examined in this paragraph.

Wave breaking parameter (γ)

Since the wave height is overestimated in the trough of the breaker bar the parameter which determines the breaker criteria is varied. The values used for γ are 0.55 (default Delft3D setting), 0.70 and γ according to Battjes and Stive (1985), see equation 2.10, which depends on the deep water wave steepness. Using the formula of Battjes and Stive (1985) γ is 0.9. This parameter is dependent on the wave steepness. Since in this experiment a stationary wave condition is used the deep water wave steepness is constant. Therefore, also the breaker parameter is constant.

Figure 5.14 shows the results of the simulations using a different γ . The default setting of γ in Delft3D and a value of 0.7 (red- and blue-line respectively) clearly results in a too early release of wave energy compared with the measurements. A value, according to Battjes and Stive (1985) for γ of 0.9 (green-line) shows comparable results for the wave height as is computed using a value for γ according to Ruessink et al (2003) (black-line). However, the wave energy is dissipated slightly earlier compared with a value according Ruessink et al resulting in an overestimation of the longshore current seaward. Furthermore, the same overestimation of the wave energy inside the bar trough is found as for Ruessink et al. Overall the Ruessink et al cross-shore varying parameter for the breaker criteria shows the best results compared with measurements for both the wave energy as for the longshore currents.

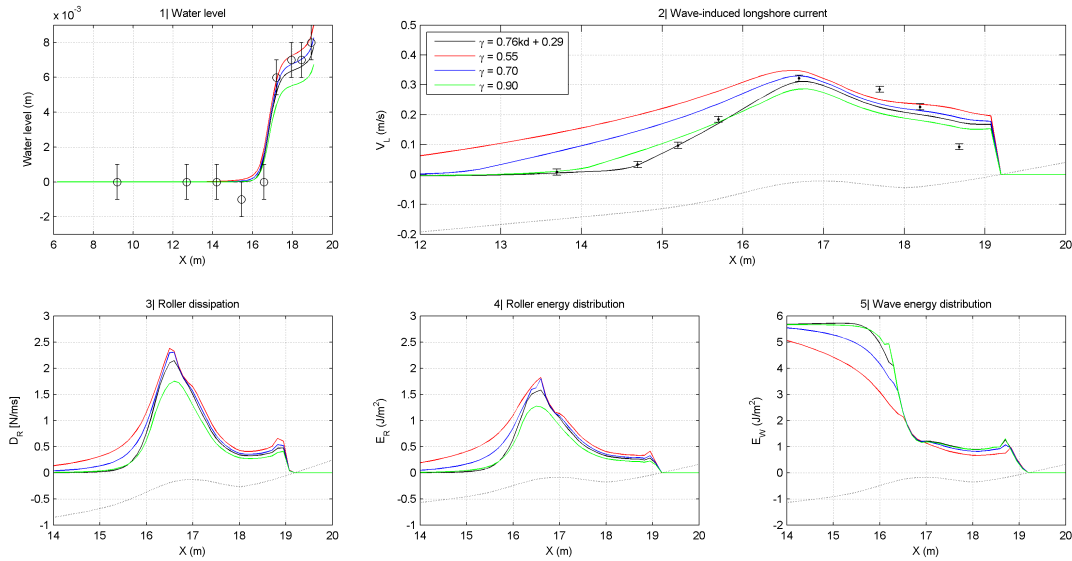


Figure 5.14 Computed values of H_{rms} , the water level and the longshore current compared with measurements for different values for different values of γ .

Alpha (α)

The parameter α increases the amount of wave energy that is dissipated due to wave breaking. Figure 5.15 shows the results for different values of α used (1 is black-line, 1.5 is red-line and 2 is the blue line). Due to the increase of wave energy dissipation the amount of roller energy (bottom middle figure) increases. This increases the roller dissipation, which is the driving force of the longshore current. Therefore the longshore current increases for higher values of α . Also the distribution of the longshore current changes. The location of the maximum longshore current is shifted slightly more seaward due to the increased dissipation of wave energy. Inside the bar trough little differences are found since here little wave breaking occurs and therefore the effects of increasing α is small. The default value of α is found to provide reasonable results compared with the measurements for both the wave height as for the longshore current.

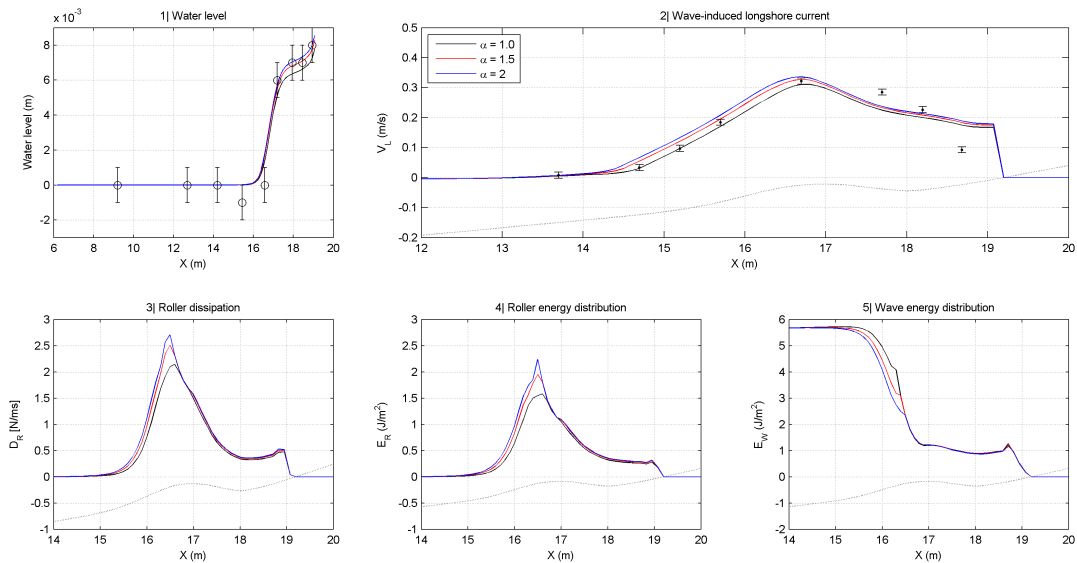


Figure 5.15 Computed values of H_{rms} , the water level and the longshore current compared with measurements for different values for different values of Alfa

5.6.4 Roller induced mass-flux

The mass-flux of the roller is the water mass, which is transferred from the wave to the roller as waves are breaking. The roller, which is transported on top of the wave towards the coast at the speed of the wave, on which it rides, carries this additional mass closer to the shore. As the roller dissipates the mass is brought back into the water column. The roller induced mass-flux thus induces an additional velocity due to the added water. This aspect is not yet taken directly into account in Delft3D. This subparagraph shows the potential effect of including the mass-flux induced by the roller. The mass-flux is determined according to:

$$mass - flux = M_r = 2 \frac{E_r}{\rho c} \quad (5.5)$$

In which,

$$M_r \quad \text{roller mass-flux} \quad [m^2/s]$$

Dividing the mass-flux through the water depth and multiplying by the wave angle results in the mass-flux induced depth-averaged alongshore current:

$$V_{M_r} = \frac{M_r}{H} \sin(\theta_w) \quad (5.6)$$

In which,

$$V_{M_r} \quad \text{velocity induced by the roller mass-flux} \quad [m/s]$$

Figure 5.16 shows the computed mass-flux in the bottom left figure and the mass-flux induced current according to (5.6) in the middle right figure. The additional mass-flux induced current is small compared to the wave-breaking induced currents. Also the location of the peak velocity and the distribution of the current velocity is similar to the by Delft3D computed current. Since the roller mass-flux is dependent on the amount of roller energy and the phase speed the shown cross-shore distribution is expected. Furthermore, the bottom right figure shows the total depth-averaged velocity, thus including the mass-flux. This velocity is gained by adding the mass-flux induced current to the depth-averaged current. In reality this is not correct since this would imply that the mass-flux induced current is not influenced by other processes (e.g. bottom friction, vertical distribution of current) and therefore is not included in the momentum and continuity equation. This figure is pure illustrative to see the order of magnitude of the roller mass-flux induced current. It can be argued that the addition is very small, but realistic and might influence the vertical distribution of the current velocity.

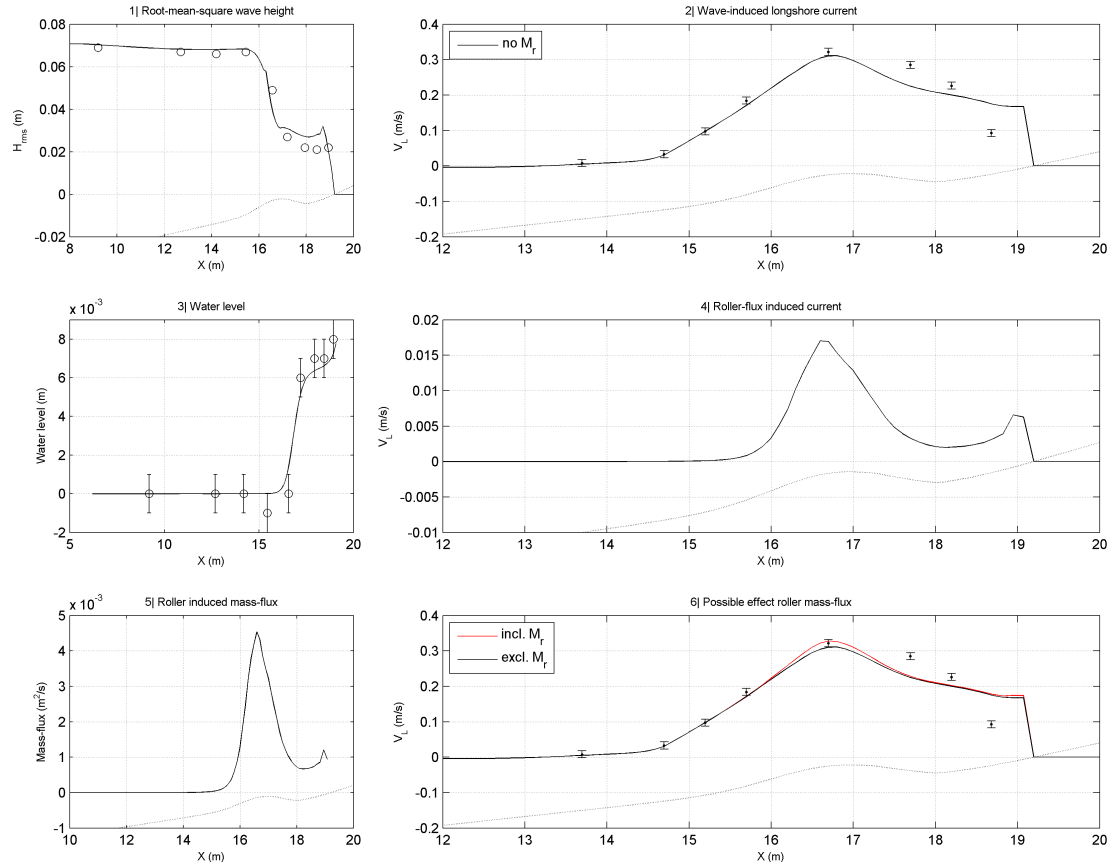


Figure 5.16 Root-mean-square wave height (subfigure 1), water level (subfigure 3), roller induced mass-flux (subfigure 5), depth-averaged velocity (subfigure 2), roller mass-flux induced currents (subfigure 4) and depth-averaged velocity including the roller mass-flux (subfigure 6)

5.6.5 Radiation stresses

In Delft3D, the wave-induced force acting on a water body is caused due to the dissipation of roller energy, as described in Appendix B. According to Longuet-Higgins and Stewart (1964), the total radiation stress induced force is determined according to (2.15). In Delft3D this same approach is used. However, for the forcing a division is made between a wave-induced force and a roller induced force, according to:

$$\begin{aligned}
 F_{w,x} &= - \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) - F_{x,r} \\
 F_{w,y} &= - \left(\frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right) - F_{y,r}
 \end{aligned}
 \tag{5.7}$$

The roller force is subtracted from the total radiation stress induced force to determine the wave force. Before the roller model was implemented the force driving the longshore currents was due to gradients in the radiation stresses; the first part between the brackets on the right side of equation (5.7). Currently, in Delft3D for a stationary computation the wave force (F_w) is switched off. This is also the reason that no water level set down is computed while measurements show a set down. The wave set down is caused by the fact that the ratio between the group velocity and the wave celerity first increases as waves propagate towards a coast. This causes a positive gradient in the radiation stress in cross-shore direction, which has to be compensated by a change in water level, a set down in this case.

To include the water level set down a computation is made including the wave part of the force. This means that the currents are computed according to equation (5.7). The result of this computation is shown in Figure 5.17. The red-line represents the computation according to equation (5.7) and the black-line represents the results for the default setting of Delft3D. Computing the currents according to equation (5.7) shows a large deviation compared with the default computation and with measurements. Compared with measurements using the default setting in Delft3D for the computation of wave-driven currents shows good results compared with measurements and will therefore be used for further computations.

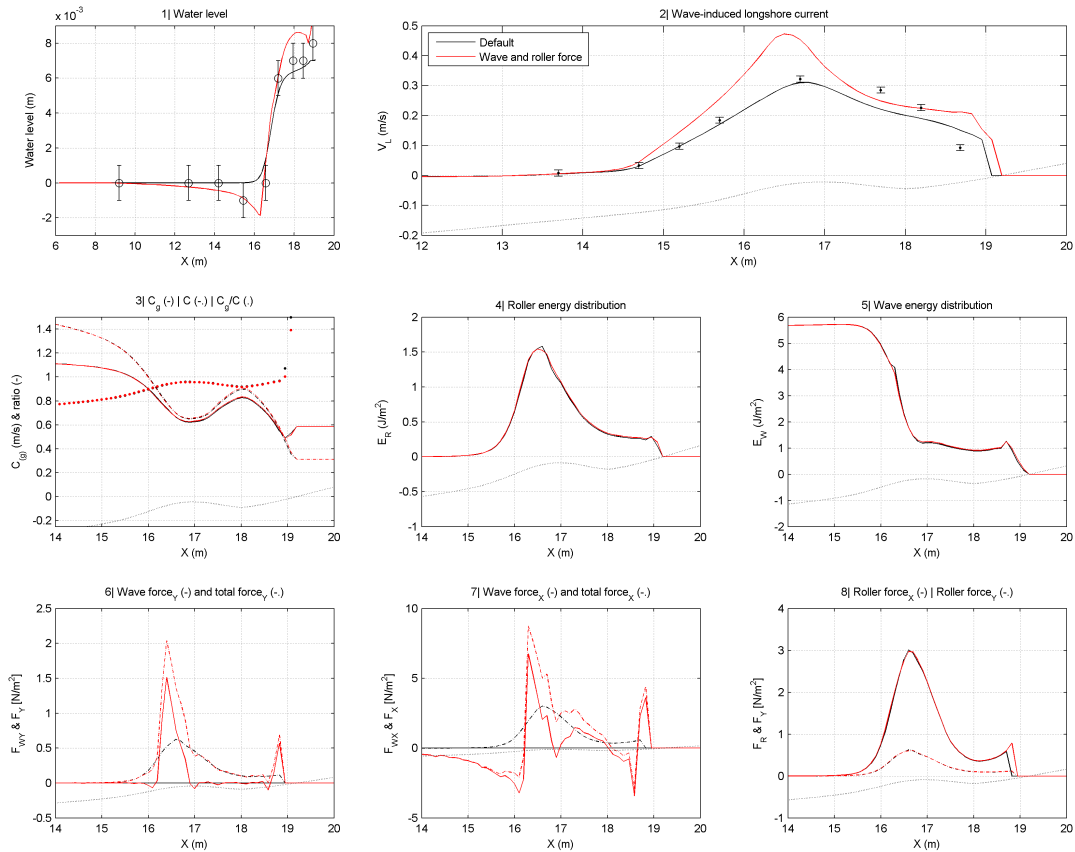


Figure 5.17 Simulation including both the wave force and the roller force (red-line) compared with default Delft3D setting (black-line)

The bottom left figure (no. 6) shows that the wave force in y -direction (red solid-line) becomes larger than 0. The wave-induced force in y -direction should be 0. Since, assuming that the derivatives in the y -direction are zero (alongshore uniformity) the second equation of equation (5.7) reduces to:

$$F_{w,y} = -\frac{\partial S_{xy}}{\partial x} - F_{y,r} \quad (5.8)$$

Since the radiation stress is computed according to:

$$S_{xy} = \sin(\alpha) \cos(\alpha) \left(\frac{c_g}{c} E + 2E_r \right) \quad (5.9)$$

The derivation in x -direction then should be, if the wave celerity (c) is placed outside the brackets and we assume that Snel's law is valid, according to equation (2.8), than the term $\frac{\sin(\alpha)}{c}$ is a constant and can be placed in front of the derivative, according to:

$$\frac{\partial S_{xy}}{\partial x} = \frac{\sin(\alpha)}{c} \frac{\partial}{\partial x} E c_g \cos(\alpha) + \frac{\sin(\alpha)}{c} \frac{\partial}{\partial x} 2 E_r c \cos(\alpha) \quad (5.10)$$

On the right hand side, the first part is equal to $-D_w$ according to the wave energy balance equation and the second part is equal to $(D_w - D_r)$ according to the roller energy balance equation (Appendix B). Furthermore, since the force induced by the roller energy dissipation is according to:

$$F_{y,r} = \frac{D_r}{c} \sin(\alpha) \quad (5.11)$$

Equation (5.8) becomes:

$$F_{w,y} = -\frac{\partial S_{xy}}{\partial x} - F_{y,r} = -\left(\frac{\sin(\alpha)}{c} (-D_w + D_w - D_r) \right) - \frac{D_r}{c} \sin(\alpha) = 0 \quad (5.12)$$

This implies that in the presence of wave-breaking, which is the source of the dissipation of roller energy, the contribution of the wave force is zero. Therefore, the results of the longshore current in Figure 5.17 for using the formulation according to equation (5.7) should be on top of the default Delft3D computations.

Figure 5.18 shows the results of a simulation based on equation (5.7), however now the term $F_{y,r}$ is set to zero, excluding the roller force. This implies that the flow is computed using the total radiation stress induced force. The black-line represents the simulation using the default Delft3D computation of the longshore current. The red-line represents the results when using the total radiation stress induced force.

The results for the water level are in good agreement compared with the measurements. In the previous figure (Figure 5.17), simulation using equation (5.7), the water level set up was overestimated compared with measurements. Excluding the roller force shows improved agreement for the water level. However, the longshore current still deviates from the current computed using the default Delft3D setting. The magnitude of the wave force (red-line, subfigure 6) is much larger than the y -component of the total force computed excluding wave forces (black-dashed-line). This causes the longshore current to be overestimated compared with the measurements.

The reason for these remarkable results is not fully understood. One possible reason might be that the

term $\frac{\partial S_{xy}}{\partial y}$ in equation (5.7) is not equal to zero due to boundary anomalies. A simulation is made

with a larger 2D grid, 19 cells width, instead of only 5. However, this resulted in exactly the same overestimation of the wave-induced currents. From this exercise it can be concluded that the translation of wave-induced forces to a flow of the water is currently done via the roller dissipation induced force. Thereby, the water level set down is not included in the computation. When including the wave force theoretically nothing changes in the computation of the longshore component of the wave force. However, in Delft3D the $F_{w,y}$ becomes larger than zero and therefore the longshore current velocity increases. This anomaly needs further attention in future research.

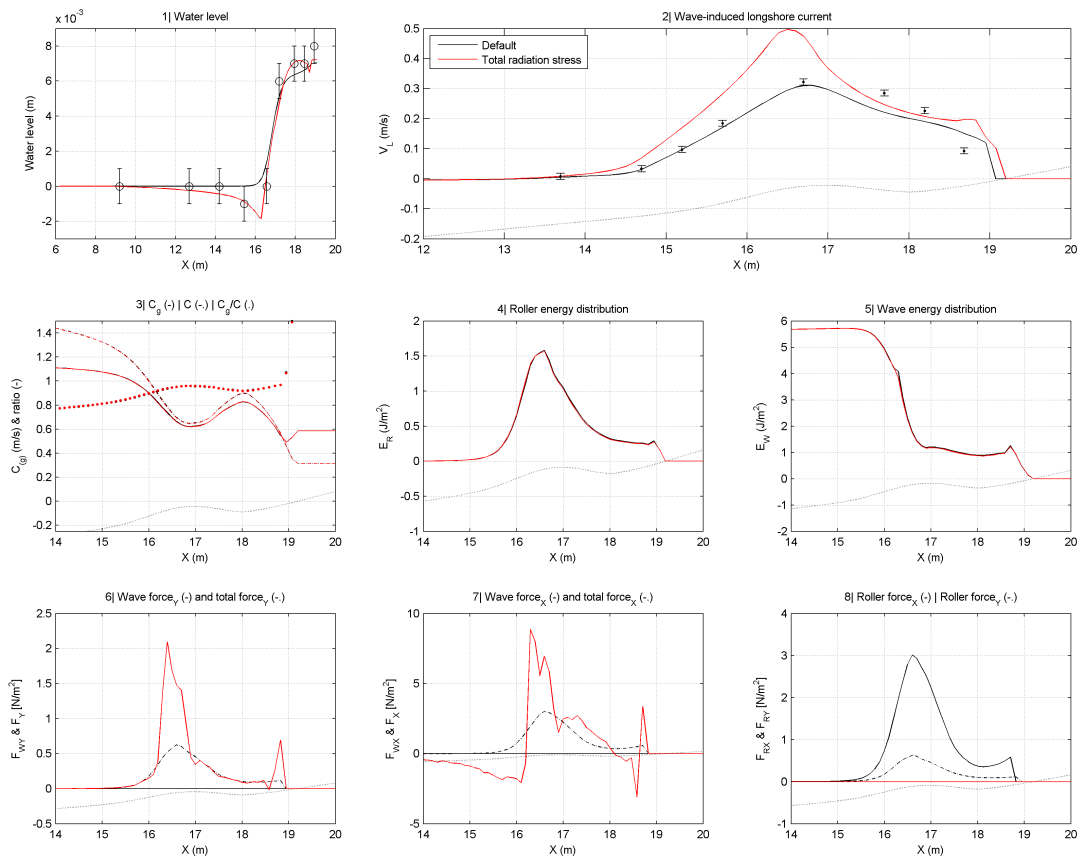


Figure 5.18 Simulation using only total radiation stress (red-line) compared with default Delft3D setting (black-line)

5.6.6 Inverse modelling technique

An integral approach, as suggested by Walstra et al (1996), makes use of a coupling between the extended wave energy and momentum balance equation to deduct the roller properties based on wave height and set up measurements. This approach is briefly discussed in Appendix B.2, for a detailed description and discussion see Walstra et al (1996). In this paragraph the inverse modelled roller properties are compared with the roller properties computed using Delft3D, for the Reniers and Battjes laboratory experiments.

To obtain the inversed results a polynomial is drawn through the measured water level and wave height. This is used as input in the inversed modelling approach. This results in the distribution of the roller energy, the roller dissipation and the slope of the roller. The values of the forces correspond to the force needed to achieve the observed water level set-down and set-up. Figure 5.19 shows that for several parameters the inversed modelled results deviate from the results computed by Delft3D. For the calibrated Delft3D model the longshore currents agree well with the measurements. However, the distribution of the roller energy shows large deviations and more remarkable the value of the roller force (bottom left figure) is considerably lower than the Delft3D computed value.

The forces, which are computed using inverse modelling, are the forces that correspond to the measured water level variation and wave height measurement. These forces should theoretically also result in the observed longshore currents if the translation of wave-induced forces to a current is valid. However, the forces obtained using the inverse modelling technique are very sensitive to the measurements of the water level and the wave height, since the forces are determined by the cross-

shore variation of the measured values. Therefore the outcome of the inverse modelled values is strongly dependent on the polynomial drawn through the measured water levels and wave heights. A simulation is made using the inverse modelled results as input in Delft3D. However, due to the abovementioned uncertainties and sensitivities to the measurements this is only described in Appendix C.

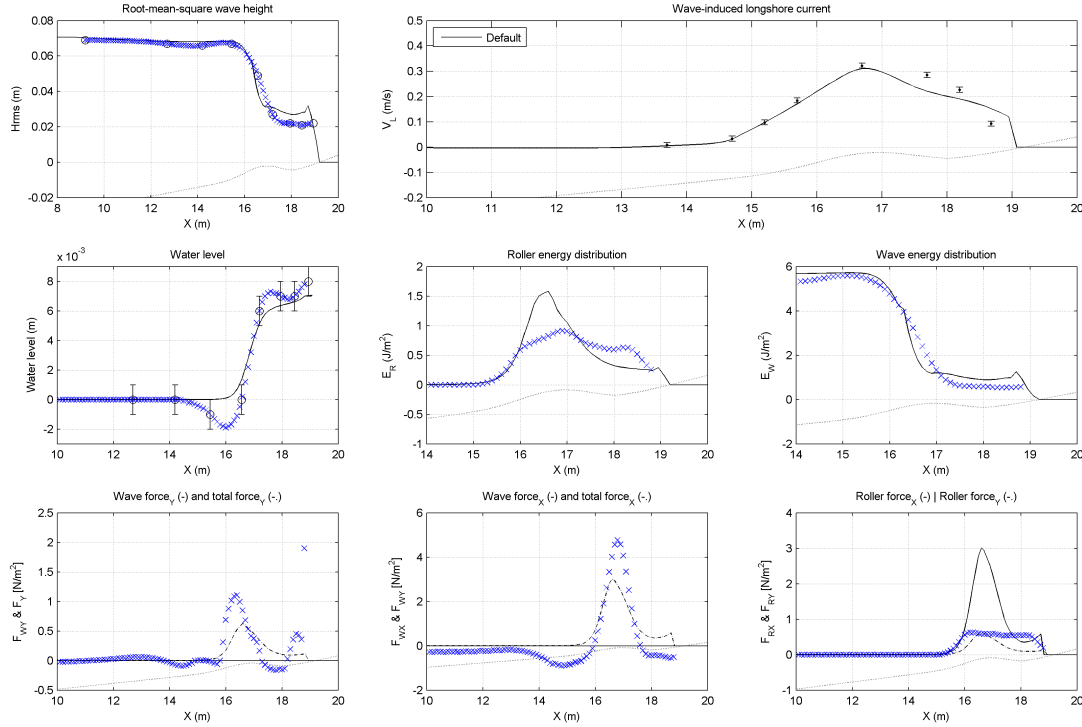


Figure 5.19 The Delft3D computed results compared with the inversed modelled (blue x) results for; the wave height (top left figure), water level (middle left figure), longshore current (top right figure), roller energy (middle figure), wave energy (middle right figure), wave force (bottom left and middle figure) and roller force (bottom right figure)

5.7 Final results

The 3D model is calibrated using the background horizontal eddy viscosity, the bottom roughness formulation, streaming and the slope of the roller. In the previous paragraph the 3D approach is calibrated and a sensitivity analysis was carried out for the 3D approach. Besides the 3D approach, also the 2DH approach is calibrated to obtain the best fit with measurements. The settings used for the 2DH and 3D computations, after calibration, are described in Table 5.2.

The main differences between the 2DH and 3D settings are the bottom roughness formulation and the value for the background horizontal eddy viscosity. For the 2DH approach a fixed Chézy value showed the best results compared with the measurements. Since the process streaming is not taken into account in the 2DH approach, without any background horizontal eddy viscosity only the momentum released by the waves onto the water would induce a current. The seaward velocity therefore is zero. To obtain a good agreement for the seaward measuring locations a background eddy viscosity of $2e-4$ is applied.

Table 5.2 Calibrated Delft3D settings for 2DH and 3D computations

Parameters	Calibrated Delft3D Settings	
	3D	2DH
Simulation time (min)	20	20
Time step (min)	0.005	0.005
Number of vertical layers (-)	15	1
Reflection parameter alpha (s ⁻²)	100	100
Roughness – White Colebrook (m)	6e-4	Chézy = 55
Background horizontal visc. (m ² /s)	0	2e-4
Threshold depth (m)	0.02	0.02
Smoothing time (min)	60	60
Roller	yes	yes
Cstbnd	yes	yes
Gamdiz (γ)	(Ruessink et al 2003)	(Ruessink et al 2003)
F _{lam} (breaker delay)	0	0
FwFac (streaming parameter)	0.1	-
β_{roller} (angle of the roller)	0.05	0.05
α (D_w calibration factor)	1	1

Figure 5.20 compares the final results obtained after the calibration for both the 2DH and 3D computed longshore currents. As reference the obtained computations by Reniers and Battjes are shown. Seaward of the breaker bar both the 3D computations of the longshore current and the 2DH computations show a good agreement with the measurements, however both 2DH (especially) and 3D underestimates the longshore current inside the bar trough. Close to the shore the 3D approach significantly overestimates the longshore current. Both the location and magnitude in 2DH and 3D of the maximum longshore current are in good correspondence with measurements. Compared with the computed results by Reniers and Battjes the seaward computation of the wave-driven longshore currents resembles measurements better, while in the bar trough the same underestimation is found. The underestimation of the longshore current in the breaker trough might be due to the underestimation of the dissipation of wave energy as the computed wave height is too high compared with the measured wave height in the bar trough. Overall, the measurements are well approximated by both the 2DH and 3D approach.

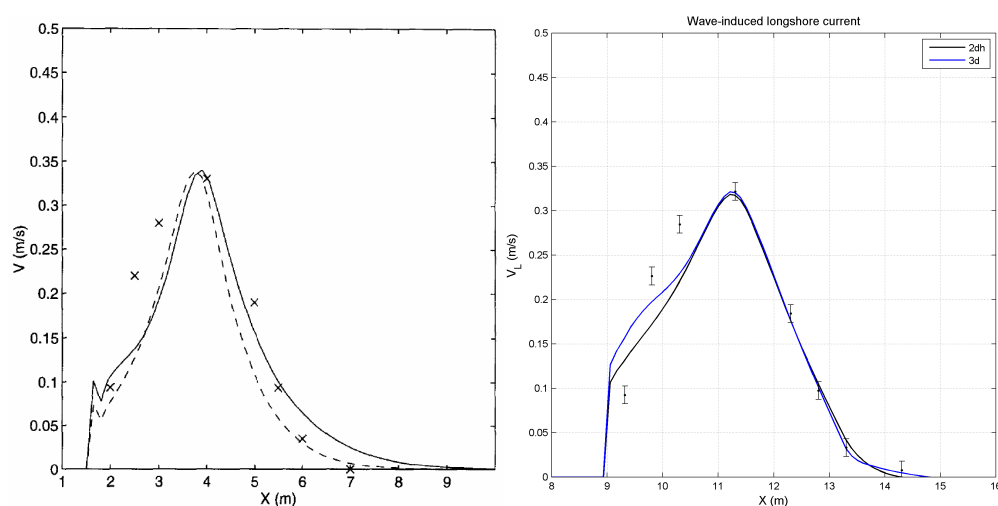


Figure 5.20 Results Reniers and Battjes (left-figure; dashed line is a linear and solid line a non-linear bottom shear stress) compared with 2DH (black-line) and 3D (blue-line) computed Delft3D longshore currents

To gain more insight in the cause of the disagreement between the computed and measured longshore current and the influence of the roller model to this discrepancy, the forcing can be hindcasted using the technique as is described in Walstra et al (1996). The inverse modelling technique is applied in the next paragraph.

5.8 Conclusions

In this Chapter the method of computing the bed shear stress by using the velocity at the computational layer just above the wave boundary layer is validated using data obtained from a laboratory experiment (Reniers and Battjes, 1997). The computed longshore currents in 3D are compared to those in 2DH and those computed in Reniers and Battjes (1997). Furthermore, an analysis is made of the model sensitivities to some variables and inverse modelling techniques are applied to validate the roller model.

The new method of computing the bed shear stress significantly reduces the dependency on the thickness of the first computational layer just above the bed. A good agreement is found up to the location of the maximum longshore currents; inside the breaker trough both the 2DH and 3D approaches underestimate the longshore current. The wave height predictions show an overestimation of the wave height in the bar trough. Apparently, wave energy dissipation due to wave breaking is underestimated resulting in too little wave energy being transferred to roller energy. This causes too little roller energy to be dissipated. The roller energy dissipation is the driving force of the longshore current and therefore might explain the underestimation of the longshore current inside the bar trough.

The conclusions from the model calibrations and sensitivity analysis:

- In the comparison with the laboratory experiment it is found that the process streaming influence the longshore current too much compared with the data. The default setting for the calibration parameter of 1 is too large. A value of 0.1 is found to be sufficient.
- Increasing the number of vertical layers beyond 15 shows no differences in computed longshore currents. However, 5 vertical layers shows inconsistencies near the shore. Using 15 layers shows good results compared with measurements and provides a detailed vertical distribution of the currents.
- In Delft3D default setting of the breaker parameter ($\gamma = 0.55$) is shows large deviations compared with measurements. The value of γ according to Ruessink et al (2003) shows the best results for the wave height compared with the measurements
- By only using the roller energy dissipation as driving force the wave set-down is not taken into account.
- Using the total radiation stress induced force as driving force of the longshore current, this longshore current is significantly overestimated. However, the water level is in good agreement with measurements.
- The effect of the roller induced mass-flux is argued to be small.

With the inverse modelling technique it is possible to determine the roller properties based on the measured water levels and wave heights. These properties are compared with the values computed using Delft3D. The inverse modelled results deviate from the results computed by Delft3D. However, the inverse modelled results are highly sensitive to the measurements. Therefore it is difficult to give a proper answer on the question if the wave forces are translated correctly to a longshore current.

Although the depth-averaged velocities are in good agreement with the measurements the vertical distribution of the longshore current cannot be verified since only one measurement location in the vertical is available. More information concerning the vertical distribution of the longshore current is

necessary to validate the vertical distribution of the longshore current and with that to fully validate the 3D computations of wave-driven longshore currents. During Sandy Duck field measurements in 1997 also measurements at different levels in the vertical are made and provide the opportunity to further determine the performance of the 3D approach. This is described in Chapter 6.

6 Validation using data from Duck 97 field measurements

Results

- *Improved method of computing the bed shear stress improves the accuracy of 3D computations compared with*
- *The 3D approach corresponds reasonable well with measurements. Longshore current is generally underestimated and the wave height is generally overestimated*
- *The longshore current near the shore is generally overestimated*
- *The wave height computed by SWAN shows good agreement with the seaward measurements. However, the decay of wave energy is better represented using the roller model*
- *The seaward located longshore current is generally underestimated. This is probably due to the fact that tide is not taken into account*
- *2DH and 3D computations show similar results*
- *Computed vertical distribution of the longshore current is generally overestimated. The agreement found between the measured and computed values is less than for the cross-shore distribution of the longshore current*
- *The vertical profiles correspond reasonably well with the measured distribution*

6.1 Introduction

The performance of Delft3D of computing the wave-driven longshore currents inside the surf zone is in the previous chapter assessed using laboratory measurements. The laboratory tests are artificial tests in which conditions are simulated excluding realistic processes (e.g. wind). The laboratory test provides the opportunity to focus on a single process, in this case wave-driven current, and validates the performance of Delft3D for that single process. The disadvantage of the laboratory experiment is the small scale of the test. In real life situation all processes occur and have to be simulated by Delft3D. Therefore, it is important make an assessment of the performance of the 3D approach for field cases.

The field experiments at Sandy Duck 97 are used for two reasons. Extensive (both time and space) field measurements are carried out, but more interesting also the currents in the surf zone are measured at different elevations above the bed. This allows for a full validation of the vertical distribution of the nearshore currents. Already some validation studies have been carried out using the data of Sandy Duck 1997 (Hsu et al., 2008; Reniers et al., 2004b; Van der Werf, 2009). Reniers et al (2004b) used the data at different elevations in the vertical and compared those with a quasi-3D model. Hsu used 2DH and Van der Werf used both 2DH and 3D modelling. However, both did not use the measurements obtained at different vertical elevations. These two studies did not use the approach of using the wave boundary layer as the point in the vertical for computing the bed shear stress. Since the 2DH approach is already extensively validated for the Duck 1997 field measurements no particular attention is paid to assess the performance of the 2DH approach.

In paragraph 6.2 the measurement study is described providing a situation description of Sandy Duck and how the measurements are carried out. In paragraph 6.3 the results of the previous comparisons with Delft3D are described. This provides useful information in setting up the Delft3D model and helps understanding the processes which are relevant at Sandy Duck. In paragraph 6.4 the set up and calibration of the Delft3D model is described and the computed results are compared with measurements obtained by Elgar et al. In paragraph 6.6 the computed vertical distribution of the longshore current is compared with measurement obtain by Thornton and Stanton.

6.2 Field measurements

6.2.1 Introduction location

The Field Research Facility (FRF) located in Duck, North Carolina conducted the field experiments at Sandy Duck in 1997. Duck is located at the east part of the USA at the Atlantic Ocean. The purpose of the Sandy Duck 97 field study was to improve fundamental knowledge of the natural processes that cause beaches to change. The primary measurement period occurred from September 22 through October 31, 1997.



Figure 6.1 Duck, North Carolina, USA located at the Atlantic Ocean (maps.google.com)

The cross-shore profile of the coast consists of crescentic bars during regular wave activity but is flattened during storm conditions. The FRF pier, which can be seen in Figure 6.1, influences the longshore current and sediment transport primarily during August as the waves then are generally south orientated. During October the waves are coming from variable directions correcting each other.

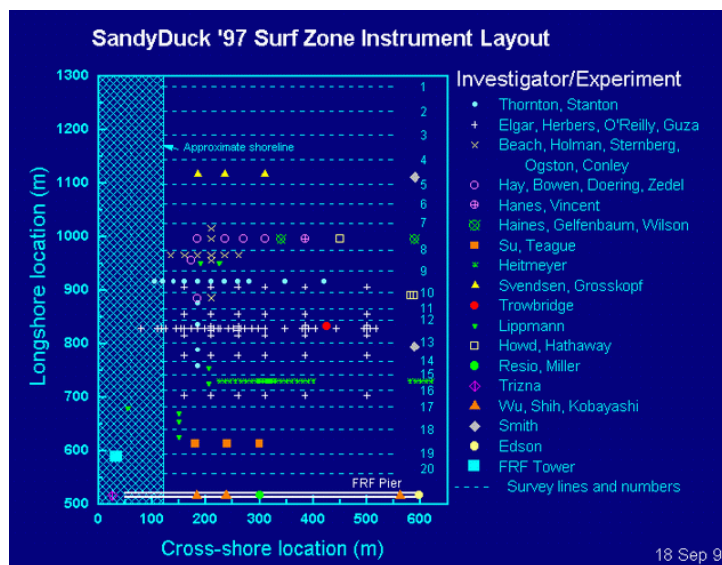


Figure 6.2 Measurements locations during Sandy Duck 1997 measurements (www.frf.usace.army.mil/sandyduck/)

The position of the measuring instruments is based on the FRF coordinate system. The zero transect is located at the Southern boundary of the FRF property and the positive directions are toward the North (longshore) and offshore (cross-shore). The vertical location (z-axis) is positive upwards and is relative to the National Geodetic Vertical Datum (NGVD), which is 0.42 meters above Mean Low Water (MLW). During this field campaign different measurements were made over the area as can be seen in Figure 6.2. During this study the data obtained by Elgar, Helgers, O'Reilly and Guza (white + signs) and the data obtained by Thornton and Stanton (blue dots) are used. The latter used a vertical array of 8 electromagnetic current meters to measure the long- and cross-shore currents.

6.2.2 Conditions Sandy Duck 1997

The waves at Sandy Duck are generally from the South in August and variable in October with the largest waves coming mostly from the North, Northeast. In contrast to Chapter 5 where the forcing of the longshore current was exclusively due to waves at Sandy Duck the currents are driven by wave, wind and tide. Figure 6.3 and Figure 6.4 show the wave conditions, tidal conditions and wind conditions during the field campaign. The top figure of Figure 6.3 shows the significant wave height. Since the focus is on wave-induced currents inside the surf zone only simulations are made for a significant wave height that exceeds 0.6 meters. The black dashed line is at 0.6 meters, the dates for which the wave height exceeds this line are the days which are used for this study.

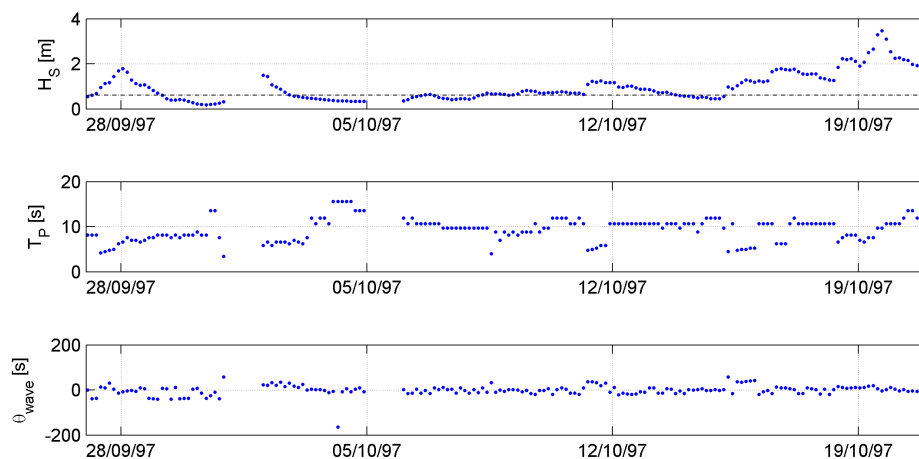


Figure 6.3 Significant wave height, peak period and wave direction during the Duck 1997 field campaign

Hsu et al and Van der Werf discussed the effect of tide on the longshore current and found that the tide has little effect on the currents inside the surf zone. These are dominated by wave-induced currents. Therefore only the vertical tide (and not the horizontal tide) is taken into account by adjusting the depth file for each simulation.

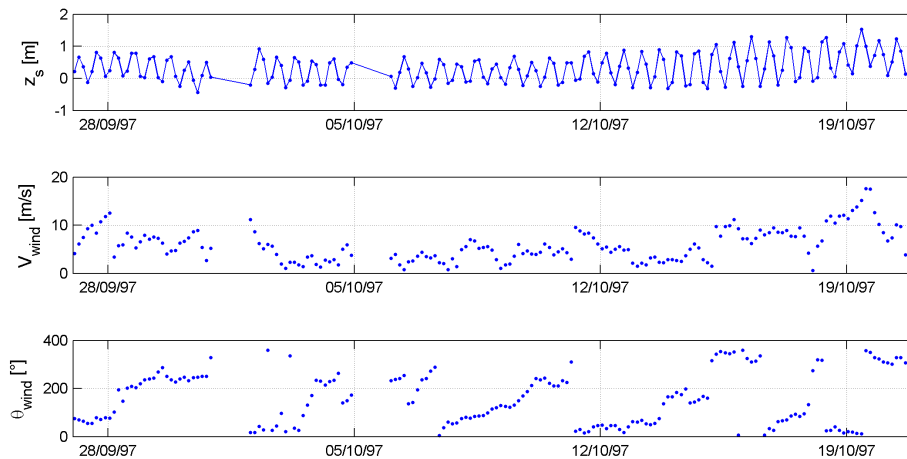


Figure 6.4 Tidal elevation, wind speed and wind direction during the Duck 1997 field campaign

Since the goal of this study is to gain more insight in the performance of 3D computations of wave-driven longshore currents inside the surf zone, only the current-measurements during times when the offshore significant wave height exceeds 0.6 meters are used to compare with computations. A smaller wave height results in a small wave-induced current. Also cases where strong rip-currents occurred are excluded in this research. Furthermore, as discussed in the previous paragraph the tide is not included since the currents are dominated by wave-induced currents. The effect of tide becomes relative larger for smaller wave heights. Since wave-induced currents are the focus of this study only cases with a wave height exceeding 0.6 meters are used. These are the same conditions as used by both Hsu et al, (2008) and Van der Werf (2009). For a list of the cases which are used for comparison see Appendix D.1.

6.3 Results previous studies

6.3.1 Reniers et al., 2004

The goal of the study by Reniers et al. was to examine the sensitivity of model output to the input of turbulent eddy viscosity and bottom friction parameters and to calibrate these parameters so that the model can be used in a predictive sense. The focus was on near bed velocities, which are important for the transport of sediments. Reniers et al. used the measurements obtained by Thornton and Stanton, which are taken at 8 different levels in the vertical, to compare with computed vertical current distributions.

The general conclusions are that strong cross-shore flows occurred under wave breaking and that the longshore current becomes more depth-uniform. Furthermore, the model is a 2DV model and is capable of describing the vertical structure of the mean flow, provided that the associated mass flux are modelled correctly and a parabolic distribution of the eddy viscosity is used. Reniers et al expected that for a depth-averaged flow model driven by a wave transformation model that includes surface rollers the near-bed velocities are computed more accurately.

6.3.2 Hsu et al., 2008

The goal of the study by Hsu et al. was to validate the wave and longshore current performance of Delft3D, to investigate the model sensitivity to model options and free parameters, to provide recommendations for operational applications and to identify limitations and / or weaknesses. Hsu used 2DH modelling.

The general conclusion of this research is that Delft3D has shown to be robust and accurate in predicting the nearshore wave heights and flows. Recommended is using the following model set up;

- Apply Roller model
- Variable gamma according to Ruessink et al (2003)
- Default Chézy bottom roughness
- Roller stress turned off at 0.4 meters to avoid spurious high currents
- Neumann boundary condition for flow side boundaries

6.3.3 Van der Werf, 2009

The goal of the study of Van der Werf was to evaluate the capability of Delft3D to predict nearshore wave and flow field and the sensitivity of these predictions to different model options. This is in correspondence with what Hsu already did, however Van der Werf also evaluated the differences between the nearshore flow field predicted by Delft3D in fully 3D and 2DH mode. Van der Werf used the abovementioned model set up as recommended by Hsu et al (2008) as a starting point.

The general conclusions of Van der Werf were that the Chézy roughness and horizontal eddy viscosity hardly influenced the predictions of the wave heights. In 2DH, Delft3D overestimates the longshore current at deep water while underestimating at shallow water. Furthermore, the maximum longshore current is overpredicted while the distance of the maximum longshore current with respect to the shore is underpredicted. The influence of the tide is negligible compared with the wave-induced currents and can therefore be excluded. In 3D the computed longshore currents are systematically lower than 2DH computed currents and are very sensitive to the adopted turbulence model and the number of vertical computational layers (note: Van der Werf did not use the modified approach of computing the bed shear stress).

6.4 Delft3D model set up

6.4.1 Introduction

The Delft3D model used by Hsu et al (2008) and Van der Werf (2009) is used in this study taking into account the conclusions and recommendations of these previous studies. The model consists of rectilinear grid of 117 grid cells in N – direction (alongshore direction) and 86 grid cells in M – direction (cross-shore direction) which corresponds to a modelled area of 1740 × 850 meters. The offshore boundary is located at the 8 meter directional wave gage array. For an overview of the modelled area see Figure 6.5. The location of the FRF pier can be seen on this figure as the deep trench in cross-shore direction located South in the area.

6.4.2 Boundary conditions

Neumann boundaries are applied at both cross-shore boundaries and at the seaward boundary (Eastern boundary) a fixed water level of zero (constant in time and space) is appointed. The vertical tide is taken into account by adjusting the depth files. At the wave boundaries a 2D wave spectrum is imposed based on the wave rider measurements at 8 meters water depth.

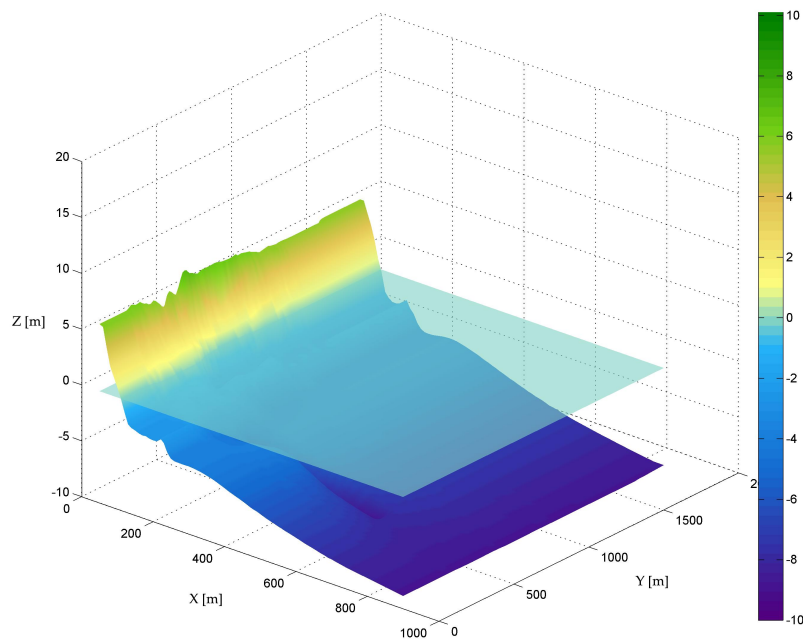


Figure 6.5 Bathymetry Sandy Duck 1997, North Carolina, USA

6.4.3 Delft3D parameter settings

The settings using in Delft3D correspond to the found settings by (Van der Werf, 2009) and the settings used in Chapter 5 (Table 6.1). The number of vertical layers is arbitrarily chosen at 15 layers to achieve a layer thickness at the top and bottom boundary of approximately 2% of the water depth using a variation factor of 1.4. Most of the parameters in Table 6.1 are already explained in paragraph 4.2. The only new parameter used is Gammax which is used to prevent unrealistic high wave forces in shallow water. During early calibration runs the 3D model stopped running. Examining the results showed that unrealistic high gradients in the water level occurred due to wave breaking. Gammax provides a maximum value for the wave force that can occur in a certain grid cell based on the local water depth and thereby preventing the 3D model from stopping.

Table 6.1 Delft3D settings Sandy Duck 1997

Parameters	Delft3D Settings	
	Van der Werf, 2009	Used Settings
Simulation time (min)	60	60
Time step (min)	0.1	0.1
Number of vertical layers (-)	varying	15
Reflection parameter alpha (s ⁻²)	100	100
Chézy roughness (m ^{0.5} /s)	60	60
Background horizontal visc. (m ² /s)	0	0
Threshold depth (m)	0.2	0.2
Smoothing time (min)	15	15
Roller	yes	yes
Cstbnd	yes	yes
Gamdis	-1	-1
F_lam (breaker delay)	0	0
FwFac (streaming parameter)	1	0.1
Betaro (angle of the roller)	0.1	0.05
Gammax	default	0.5

6.5 Data Elgar et al

6.5.1 Introduction

For Duck the measurements cover a period of approximately a month and as mentioned before only the cases for which the significant offshore wave height exceeds 0.6 meters are taken into account (see Appendix D.1). To quantify the performance of the 3D computations the root-mean-square error, the correlation coefficient (r^2), and the slope of the linear least-square-fit is used. The root-mean-square error is the square-root of the mean of the squared error, according to:

$$RMS = \sqrt{\frac{1}{N} \sum_i^N (X_i - Y_i)^2} \quad (6.1)$$

In which,

X_i computed data point

Y_i measured data point

The correlation coefficient is a coefficient that gives the quality of a least-squares fitting to the measured data, according to:

$$\begin{aligned} r^2 &= \frac{SS_{xy}}{SS_{xx} SS_{yy}} \\ SS_{xx} &= N \text{ var}(X) \\ SS_{yy} &= N \text{ var}(Y) \\ SS_{xy} &= N \text{ cov}(X, Y) \end{aligned} \quad (6.2)$$

In which the subscript x and y denotes the computed and measured values respectively. N denotes the amount of data points. To check whether the computations over- or underestimate the measurements also the slope of the linear least-square-fit ($Y=mX_i$) is determined according to (forced through zero):

$$m = \frac{\sum_{i=1}^n X_i Y_i}{\sum_{i=1}^n Y_i^2} \quad (6.3)$$

In which,

X_i computed data

Y_i measured data

If the m value is larger than 1 this implies that the computed values are overestimated compared with measurements and if the value is smaller than 1, this implies an underestimation.

The performance is determined for both the longshore current and the wave height. Since the 2DH approach is already calibrated by Hsu et al (2008) and Van der Werf (2009) using the same data as in this study no particular attention is given to further improve the 2DH computations. The 3D approach has not been calibrated and therefore a calibration is performed. The results, after calibration, obtained

using the 2DH and 3D approach are compared with each other. Furthermore, as a sensitivity analysis, in this chapter also the wave computations by the roller model and the Wave-module (SWAN) are compared since the dissipation of the organised wave energy drives the nearshore currents.

6.5.2 Calibration

In Chapter 5 the free parameters within the Flow-module of Delft3D are used to calibrate the model and to determine the sensitivity of the computed currents to these parameters. Not all of these free parameters are used to calibrate the model. Only the most relevant processes are calibrated to give a good estimate of the performance of Delft3D of computing the wave-driven currents. The parameters which are used for the calibration are those found in Chapter 4 to have a large influence on the longshore current:

- Chézy coefficient
- background eddy viscosity
- roller slope

Furthermore, the calibration parameter (α) for wave dissipation is varied to try to increase the accuracy of the computed longshore currents by increasing wave dissipation. This parameter is used since during the first computations it is found that the wave height close to the shore is overestimated. Also a comparison is made between the wave heights computed using the roller model and those computed by SWAN. The goal of the calibration is to obtain accurate computations of the longshore current compared with the measured longshore current.

First the Chézy coefficient is varied. The Chézy value that provided the best fit is used in calibrating the background eddy viscosity. The best value for the background eddy viscosity is used to determine the best value for the roller slope.

Chézy coefficient

Figure 6.6 shows the cross-shore distribution of the longshore current, wave height and water depth for the case at October 2nd 1997 at 1600 hours for Chézy values of 55 m^{0.5}/s (black-line) and 60 m^{0.5}/s (red-line). A Chézy roughness of 60 m^{0.5}/s shows better results in this particular case for the longshore current.

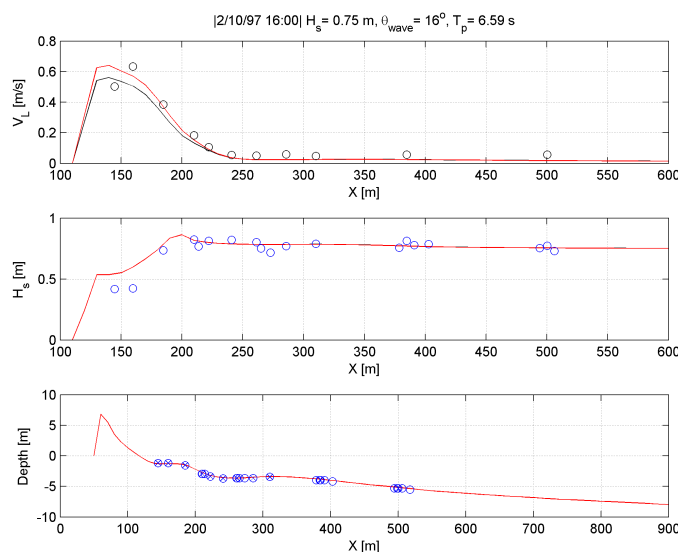


Figure 6.6 Computed results compared with measurements for Chézy is 55 m^{0.5}/s (black-line) and 60 m^{0.5}/s (red-line)

To determine the overall effects of the different Chézy values the abovementioned root-mean-squared error, the correlation factor and the slope of the linear least-square-fit is determined and shown in Figure 6.7. The left figure is for a Chézy value of $55 \text{ m}^{0.5}/\text{s}$ and the right figure for a Chézy value of $60 \text{ m}^{0.5}/\text{s}$. For both Chézy values the rms-error and the correlation factor show similar results. However, the slope of the linear least-square-fit is different. In the case of a Chézy value of $55 \text{ m}^{0.5}/\text{s}$ the slope is 0.81 and for a Chézy value of $60 \text{ m}^{0.5}/\text{s}$ the slope is 0.94. This implies that for both Chézy values the computed longshore current, averaged for all 46 cases, is underestimated. However, a Chézy value of $60 \text{ m}^{0.5}/\text{s}$ results in a considerably reduced underestimation. A Chézy value of $60 \text{ m}^{0.5}/\text{s}$ corresponds better with measurements based on the slope of the linear least-square-fit and the correlation factor. This value is used for the further calibration. A Chézy value of $65 \text{ m}^{0.5}/\text{s}$ would probably reduce the underestimation further, but also might cause an overestimation. For the purpose of this study a Chézy value of $60 \text{ m}^{0.5}/\text{s}$ is found to be satisfying.

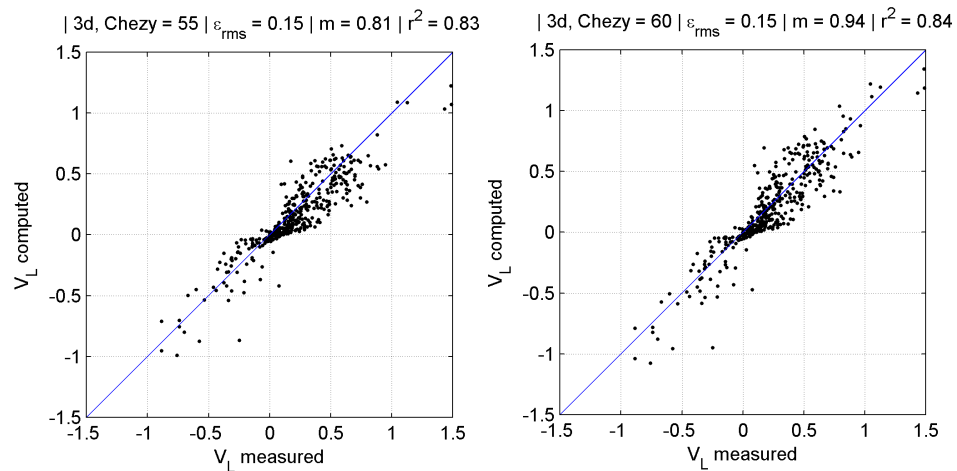


Figure 6.7 Comparison between measured and computed longshore currents for different values of the Chézy roughness coefficient

The wave height predictions show no deviation as the wave height is independent of the bottom friction as also is mentioned in paragraph 5.5.2, but are for both values in reasonably good agreement with the measurements. Figure 6.8 shows the computed results for both Chézy values. The differences between both computations are negligible and both show a slight overestimation ($m = 1.06$) while there is a relative high correlation between the measured and computed wave heights (0.96). Furthermore, a root-mean-square error of 0.15 centimeters is found. Looking more closely at the figure, the computed values are generally overestimated for small measured wave height (up to 1.5 m), while for larger measured wave heights the (larger than 1.5 m) the computation tend to underestimate the measured wave height. It is difficult to determine why the high measured waves are at certain cases underestimated by Delft3D but this might be due to the fact that only dissipation due to wave-breaking is taken into account in the roller model. Wave energy dissipation due to white-capping (mostly at deeper waters) and bottom friction (mostly at shallower water) are not taken into account.

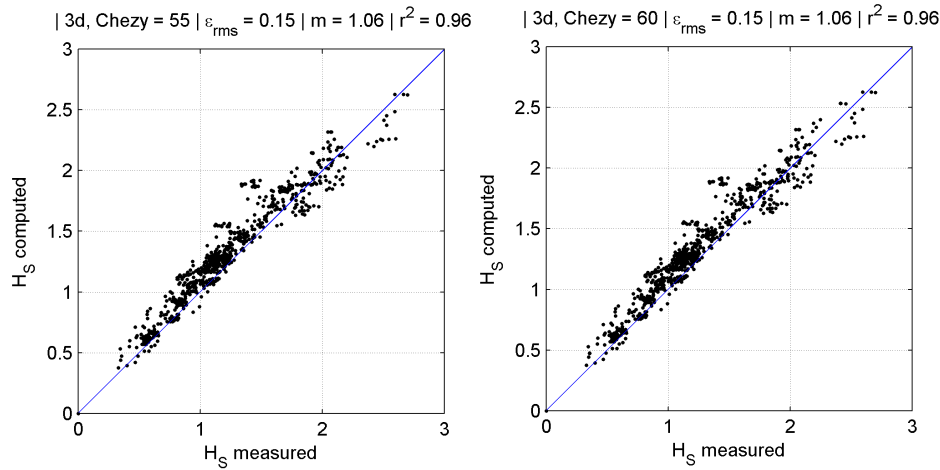


Figure 6.8 Comparison between measured and computed significant wave height for different values of the Chézy roughness coefficient

Figure 6.9 shows the case of October the 20th at 10.00 am. The wave height is underestimated over the whole cross-shore section. However, this underestimation looks more or less constant over the whole cross-shore section and the wave energy decay represents the measured decay reasonable. Therefore, either too much wave energy dissipation occurred before the waves entered the considered area (as plotted in the figure) or the imposed wave spectrum is not correct.

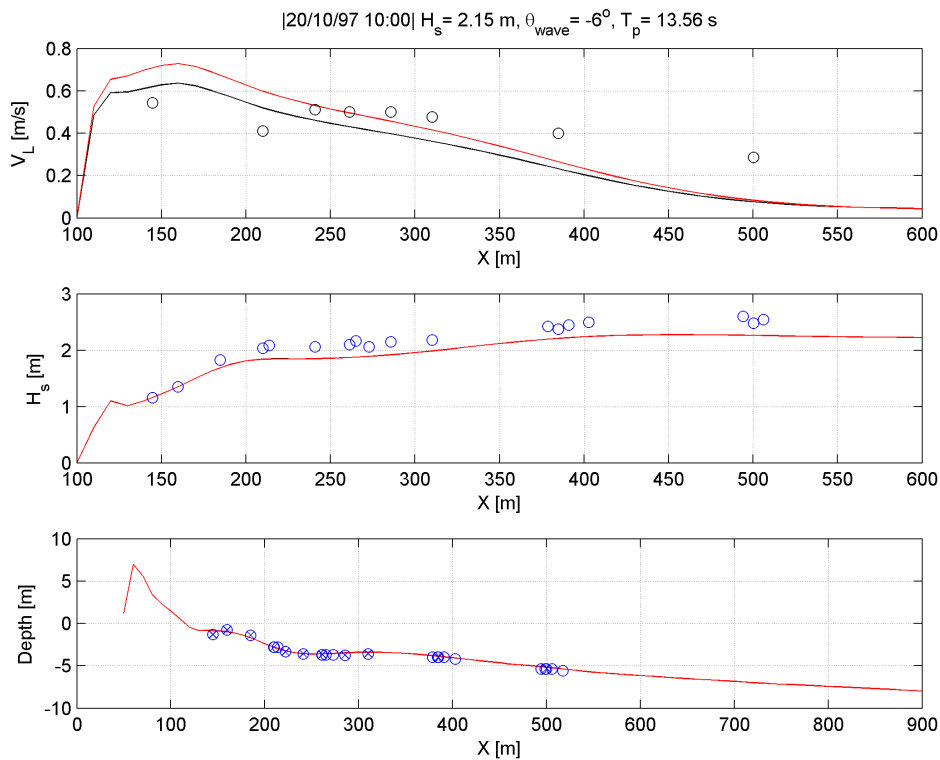


Figure 6.9 Computed results compared with measurements for Chézy is 55 $m^{0.5}/s$ (black-line) and 60 $m^{0.5}/s$ (red-line) for a offshore significant wave height of 2.15 meters

Based on these simulations a Chézy value of 60 is applied for further calibration.

Background eddy viscosity

A background eddy viscosity values of $0 \text{ m}^2/\text{s}$ and $0.5 \text{ m}^2/\text{s}$ are used. These values are chosen based on the earlier findings of Van der Werf (2009) and the validation of the Reniers and Battjes laboratory test in Chapter 4. Van der Werf (2009) found that increasing the background eddy viscosity reduces the accuracy of the computed data.

As described in Chapter 4 the background eddy viscosity spreads the cross-shore velocity profile, reducing the maximum longshore current velocity and increasing the current velocity sea- and shoreward. This can be observed in Figure 6.10 for the same case as in Figure 6.6. The red-line denotes a background eddy viscosity of $0.5 \text{ m}^2/\text{s}$ and the black-line a background eddy viscosity of $0 \text{ m}^2/\text{s}$. The red-line clearly shows more horizontal exchange of momentum compared with the black-line. The significant wave height predictions show no deviation for a different value for the background horizontal eddy viscosity.

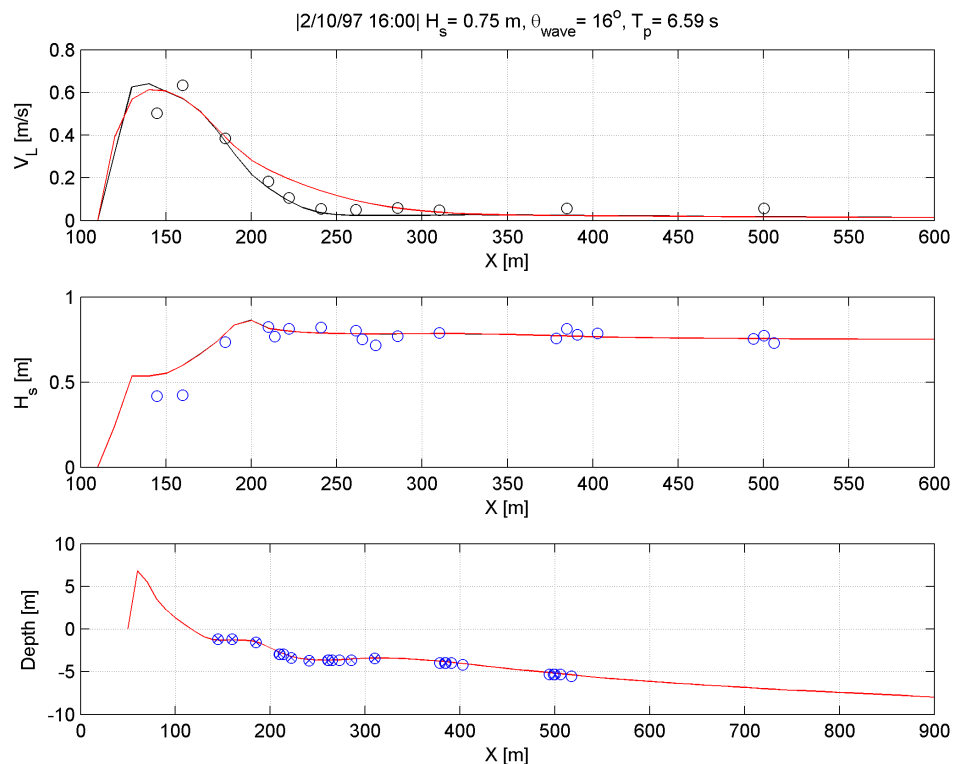


Figure 6.10 Computed results compared with measurements for a eddy viscosity of $0 \text{ m}^2/\text{s}$ (black-line) and $0.5 \text{ m}^2/\text{s}$ (red-line)

Figure 6.11 shows the computed currents compared with the measured currents for all cases. The left figure shows the results for an eddy viscosity of $0 \text{ m}^2/\text{s}$ and the right figure shows the results for an eddy viscosity of $0.5 \text{ m}^2/\text{s}$. For both simulations a Chézy value of $60 \text{ m}^{0.5}/\text{s}$ is used. No difference in the rms-error is found if the eddy viscosity is increased and the correlation coefficient decreases slightly. Furthermore, the slope of the least-square-fit also remains constant. A reason for this might be that the higher velocities are predicted slightly lower while the more offshore located velocities are computed higher, thereby for all cases the difference remains the same. This is examined further in Figure 6.12 and Figure 6.13.

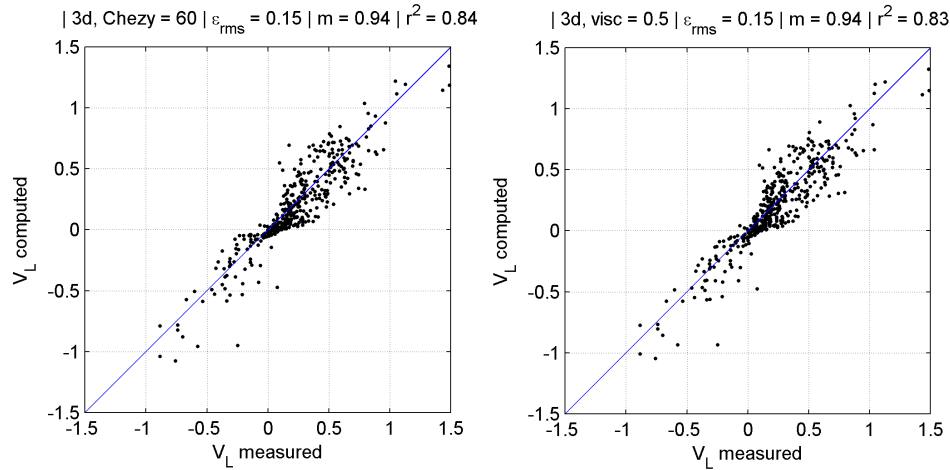


Figure 6.11 Comparison between measured and computed longshore currents for different values of the background eddy viscosity (left figure is $0 \text{ m}^2/\text{s}$, right figure is $0.5 \text{ m}^2/\text{s}$) for a Chézy value of $60 \text{ m}^{0.5}/\text{s}$

Figure 6.12 and Figure 6.13 show the computed currents compared with the measured current for each individual measuring location. The locations of the measurements are denoted in the bottom figure. Number in the title per figure represents the number located in the bottom figure for each cross-shore location of the measurements.

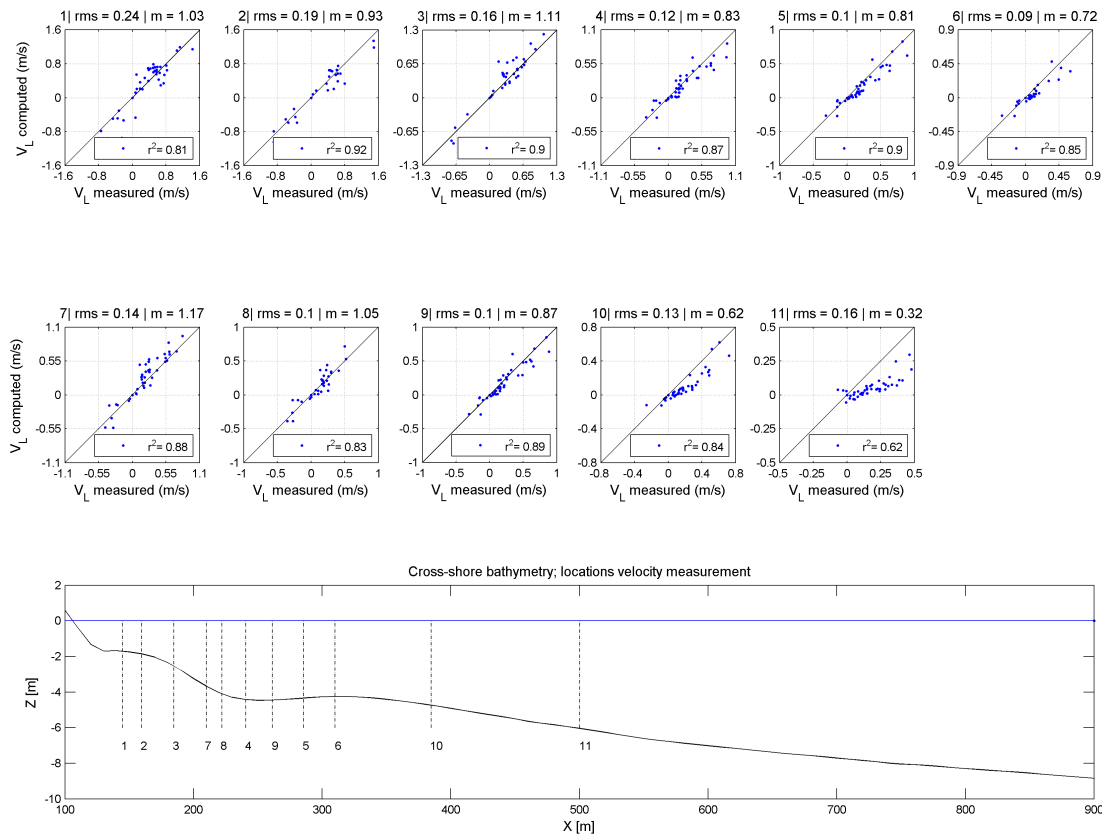


Figure 6.12 Computed longshore current compared with measurements per cross-shore location of the individual measurement location for a background eddy viscosity of $0 \text{ m}^2/\text{s}$

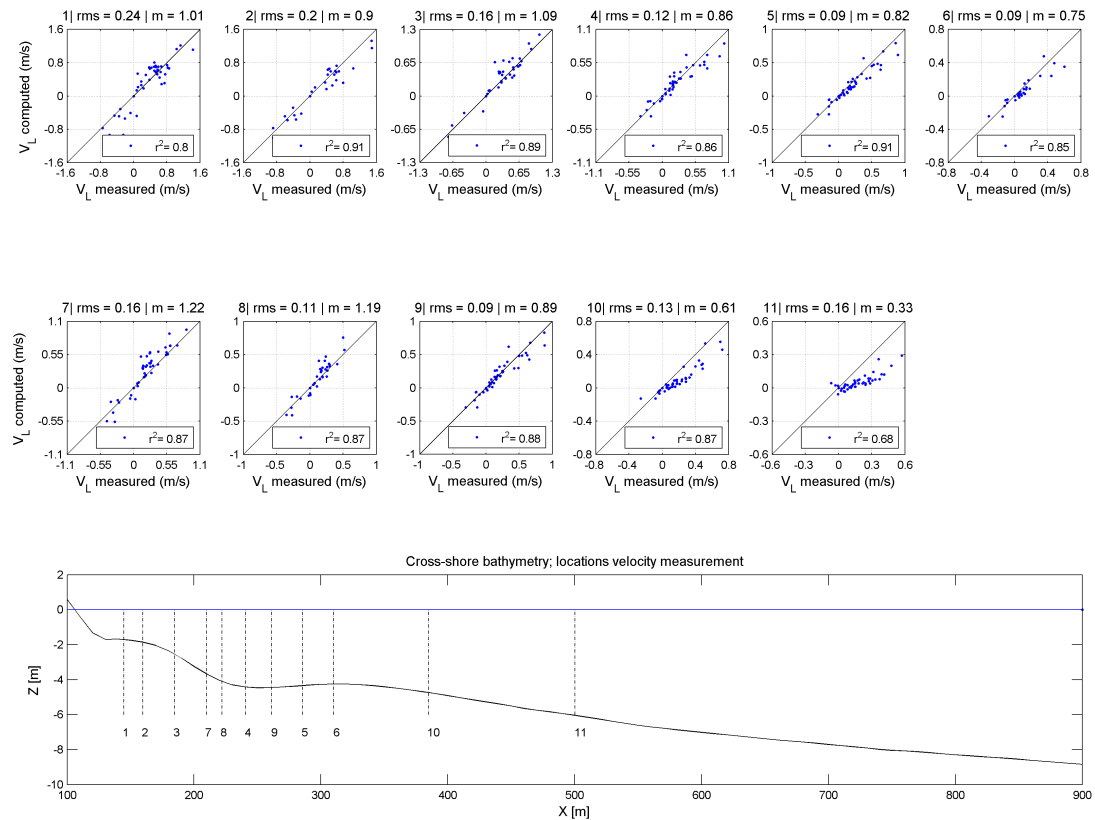


Figure 6.13 Computed longshore current compared with measurements per cross-shore location of the individual measurement location for a background eddy viscosity of $0.5 \text{ m}^2/\text{s}$

The slope of the linear least-square-fit (m) denotes whether the measured currents are either under- or overestimated. The cross-shore distribution of the value m is shown in Table 6.2 (first two columns for different values of the background eddy viscosity). A value for the background eddy viscosity of $0.5 \text{ m}^2/\text{s}$ shows a lower value of m for the measurement locations close to the shore (red-marked) and a higher value of m for measurement location further seaward (green-marked) than a value for the background eddy viscosity of $0 \text{ m}^2/\text{s}$. The increase in horizontal mixing results in more momentum transferred horizontally resulting in an increased spread of the cross-shore distribution of the longshore current.

Furthermore, Figure 6.12 and Figure 6.13 clearly show that the longshore current is strongly underestimated seaward for both computations (subfigures 10 and 11 in both figures show a large deviation compared with the black-line). There are several possible explanations for this large underestimation. One would be an underestimation of the process streaming (as extensively described in Chapter 4). In Figure D.1 of Appendix D, a same figure is made as Figure 6.13. The value of the linear least-square-fit is shown in the third column of Table 6.2. The result of increasing the effect of the process streaming is more visible for the more seaward located measurement locations. As discussed in the previous Chapters, the effect of streaming is relatively large for location where the wave height is large.

Another reason for the underestimation is might be due to the exclusion of the tide in this model. The tidal velocity is generally larger for deeper water since the flow is less reduced due to bottom friction. Therefore, the effect of not taking the tide into account is relative larger for deeper water. Since overestimation seaward of the surf zone is less relevant.

Table 6.2 Cross-shore distribution of the linear-square-fit slope for the values 0 m²/s and 0.5 m²/s of the background eddy viscosity

Locations	V _L v _h = 0.0 m ² /s	V _L v _h = 0.5 m ² /s	V _L Fwfac = 0.5 m
	m	m	m
<i>all locations</i>	0.94	0.94	0.93
1 (x=145)	1.03	1.01	1.01
2 (x=160)	0.94	0.90	0.93
3 (x=185)	1.11	1.09	1.09
7 (x=210)	1.17	1.23	1.18
8 (x=222)	1.05	1.18	1.13
4 (x=241)	0.83	0.86	0.84
9 (x=261)	0.87	0.89	0.87
5 (x=286)	0.81	0.82	0.81
6 (x=310)	0.72	0.75	0.79
10 (x=385)	0.62	0.61	0.63
11 (x=500)	0.32	0.33	0.35

The wave height for both values of the background eddy viscosity is shown in Figure 6.14. Again little differences are found between a background horizontal eddy viscosity of 0 m²/s and 0.5 m²/s since the eddy viscosity influences only the velocity. Due to the online-coupling of the Wave- and Flow-module the wave height computation is slightly influenced. Only the correlation decreased slightly for a background horizontal eddy viscosity of 0.5 m²/s.

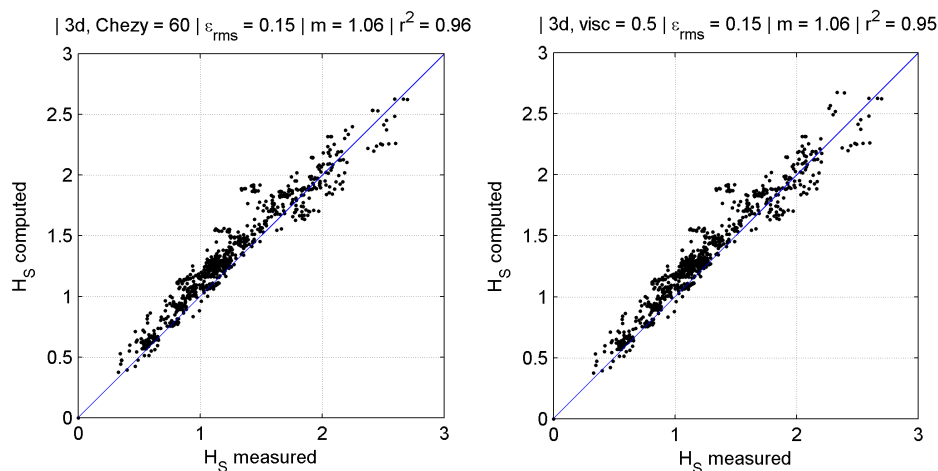


Figure 6.14 Comparison between measured and computed significant wave height for different values of the background eddy viscosity (left figure is 0 m²/s, right figure is 0.5 m²/s) for a Chézy value of 60 m^{0.5}/s

Since the longshore current is hardly affected by the increase of the background horizontal eddy viscosity coefficient a background eddy viscosity of 0 m²/s is used for further computations.

Roller slope

The angle of the roller slope has proved (Chapter 4) to be an important calibration factor. A value of 0.05 is found to be in good agreement with the measured data for the laboratory tests of Reniers and Battjes. The default setting within Delft3D is 0.10. The effect of the different roller slopes is examined for the Sandy Duck measurements. For the roller slope the values 0.05, 0.10 and a cross-shore varying

value according to Walstra et al (1996) are examined. Figure 6.15 shows the results for October 2nd 16:00. The main differences are shown at the locations around the maximum longshore current.

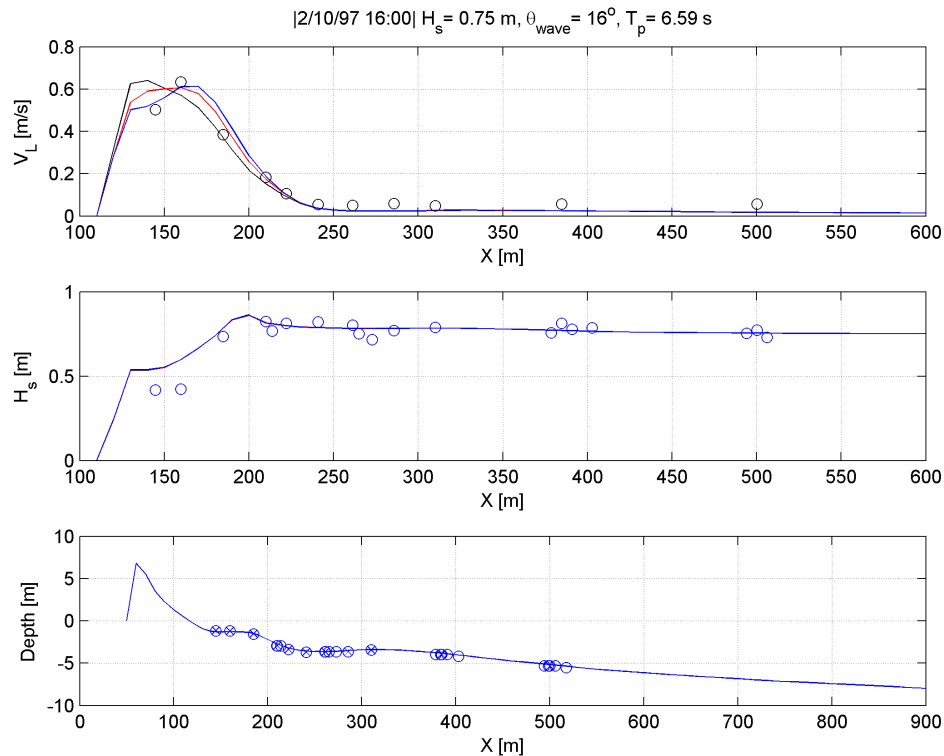


Figure 6.15 Computed results compared with measurements for a roller slope of 0.05 (black-line), 0.10 (red-line) and according to Walstra et al 1996 (blue-line)

The results of varying the roller slope are summarized in Table 6.3 for the different cross-shore location of the measurements. The corresponding figures for the different values of the roller slope are shown in Appendix D.2. Inside the surf zone ($X < 250$ m), the roller slope values of 0.10 and according to Walstra et al (1996) show a larger rms-error than for a value of 0.05. This is also shown in Figure 6.16 where the cross-shore distribution of the rms-error and the slope of the least-square-fit are shown. For all values of the roller slope a large rms-error is found near the shore (location 1). The cross-shore distribution of the rms-error and the slope of the least-square-fit are shown in Figure 6.16. A roller slope of 0.05 shows the lowest rms-error near the shore compared with the other values for the roller slope. Furthermore, the slope of the least-square-fit for a roller slope of 0.05 also shows the best results for $X < 250$ m. For the case shown in the figure above, the surf zone is from $X = 100$ m to $X = 250$ m. This implies that a roller value of 0.05 shows the most accurate results inside the surf zone based on the rms-error and the slope of the least-square-fit.

Table 6.3 Computed currents compared with measurements per location for different values of the roller slope (β_r)

Locations	V_L $\beta_r = 0.05$			V_L $\beta_r = 0.10$			V_L $\beta_r = -1$		
	ϵ_{rms}	m	r^2	ϵ_{rms}	m	r^2	ϵ_{rms}	m	r^2
all locations	0.15	0.94	0.84	0.16	0.98	0.83	0.16	1.00	0.84
1 ($x=145$)	0.24	1.03	0.81	0.24	1.03	0.82	0.25	1.03	0.81
2 ($x=160$)	0.19	0.94	0.92	0.21	0.95	0.90	0.24	1.03	0.90
3 ($x=185$)	0.16	1.11	0.90	0.23	1.24	0.87	0.24	1.24	0.86
7 ($x=210$)	0.14	1.17	0.88	0.18	1.23	0.85	0.19	1.23	0.83
8 ($x=222$)	0.10	1.05	0.83	0.11	1.18	0.84	0.12	1.21	0.85
4 ($x=241$)	0.12	0.83	0.87	0.12	0.85	0.87	0.13	0.84	0.86
9 ($x=261$)	0.10	0.87	0.89	0.10	0.91	0.90	0.10	0.91	0.88
5 ($x=286$)	0.10	0.81	0.90	0.10	0.87	0.91	0.10	0.88	0.90
6 ($x=310$)	0.09	0.72	0.85	0.08	0.84	0.86	0.08	0.89	0.86
10 ($x=385$)	0.13	0.62	0.84	0.12	0.74	0.89	0.11	0.80	0.90
11 ($x=500$)	0.16	0.32	0.62	0.16	0.39	0.70	0.15	0.42	0.70

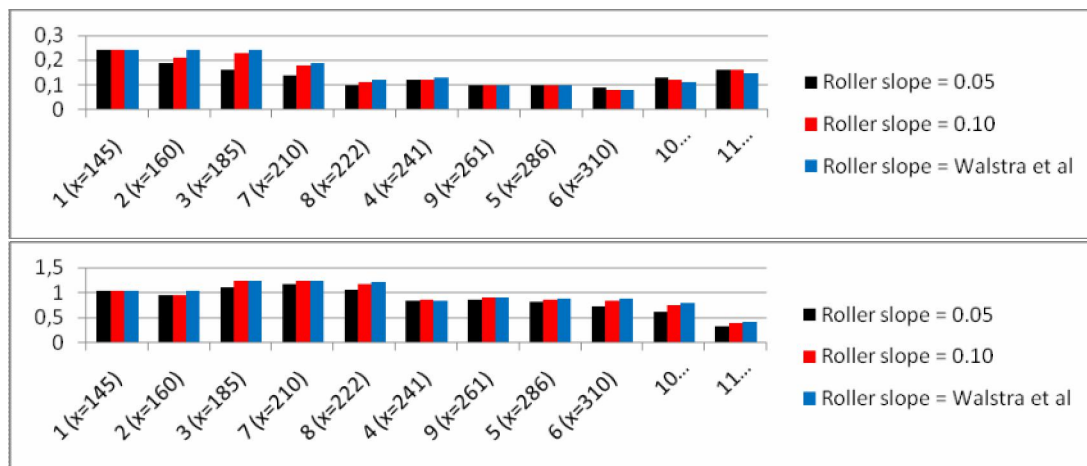


Figure 6.16 Cross-shore distribution of the rms-error (top figure) and the slope (m) of the least-square-fit (bottom figure)

Calibration parameter (α)

Since the wave height computation is generally overestimated for large wave heights the wave dissipation calibration parameter (α) is varied. Since the goal is to obtain accurate results the effect of different values of α on the longshore current is briefly described. Figure 6.17 shows the results for different values of α . Only inside the surf zone the effect of α is noticed since only in the surf zone wave breaking occurs. Increasing α has only a small effect on the longshore current and wave height computations. According to Figure 6.18 the longshore currents for a value for α of 1 shows the lowest rms-error and slope of the least-square-fit closest to 1, for the locations in the surf zone.

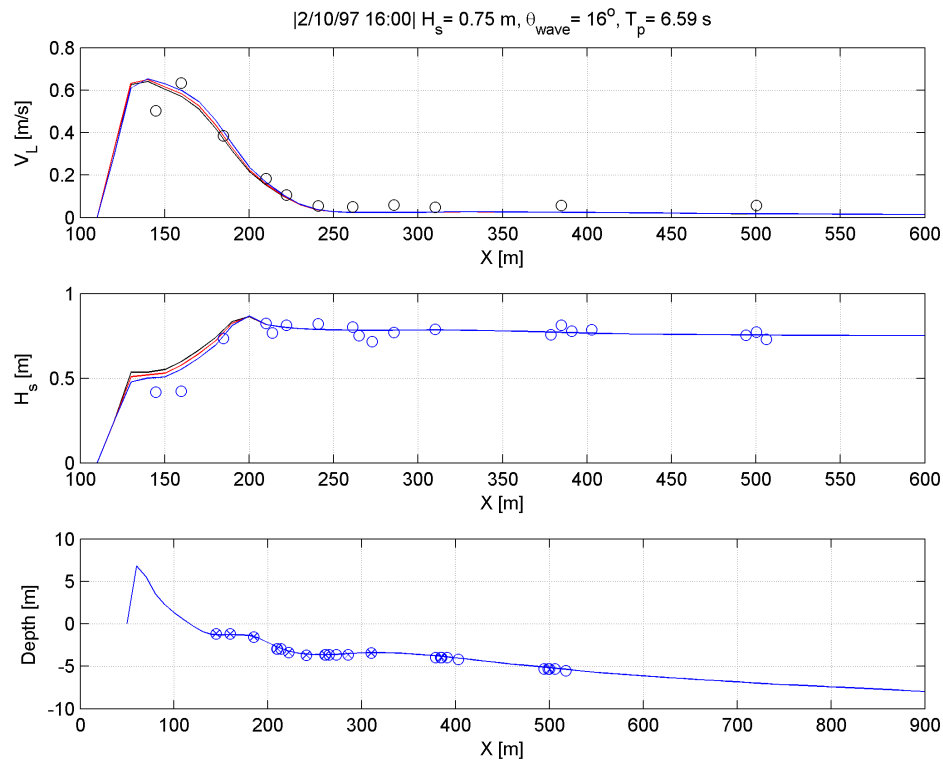


Figure 6.17 Computed results compared with measurements for a value of α of 1.0 (black-line), 1.2 (red-line) and 1.5 (blue-line)

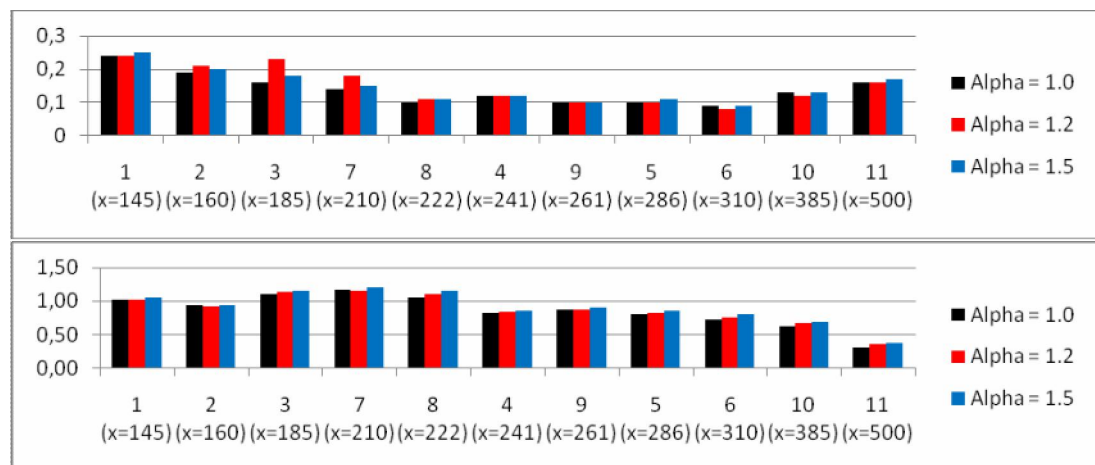


Figure 6.18 Cross-shore distribution of the rms-error (top figure) and the slope (m) of the least-square-fit (bottom figure)

Roller model and SWAN

The roller model in general seems to overestimate the wave height. The roller model is applied within the flow grid; the boundary conditions for the roller model are acquired using SWAN. SWAN is applied within the wave grid and although the wave grid is larger than the flow grid it also computes the wave height inside the flow grid. It is interesting to compare the computed wave height by the roller model with the wave height obtained by SWAN. Note; no further calibration for SWAN or the roller model is applied than mentioned above.

Figure 6.19 shows the results of the SWAN computation (black-line) compared with the roller model computed values (red-line) for an arbitrary case (October 2nd at 16.00). The wave energy computed by

the roller model is converted into the H_{rms} (according to equation (2.3)) and multiplied by $\sqrt{2}$ to obtain the significant wave height. In this particular case the roller model shows a better decay of wave energy compared with SWAN. Also the seaward predicted wave heights seem in better agreement for the roller model. Figure 6.20 shows the SWAN and roller model computed wave height compared with measurements for all 46 cases. The slope of the linear least-square-fit m shows a slightly less overestimation for the SWAN computed wave heights, however the correlation between the measured and computed wave height is slightly lower for SWAN. Furthermore, SWAN shows some more overestimation of the wave height for the both low and high waves. However, the SWAN computed wave heights show less underestimation for high waves heights than the roller model does.

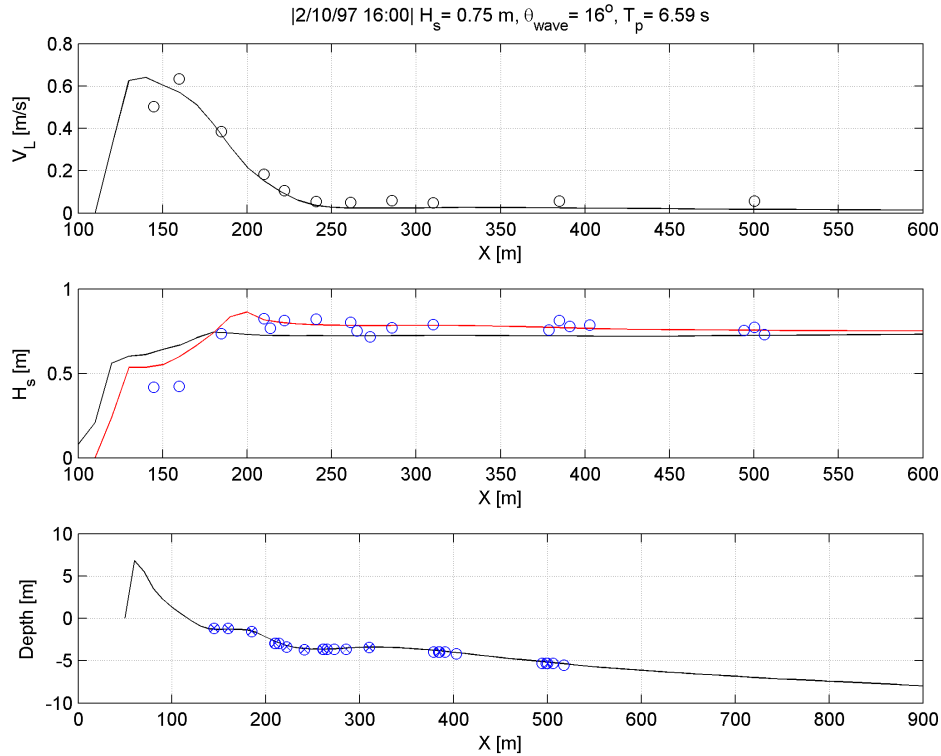


Figure 6.19 Computed results compared with measurements; wave height by SWAN (black-line) and the roller model (red-line)

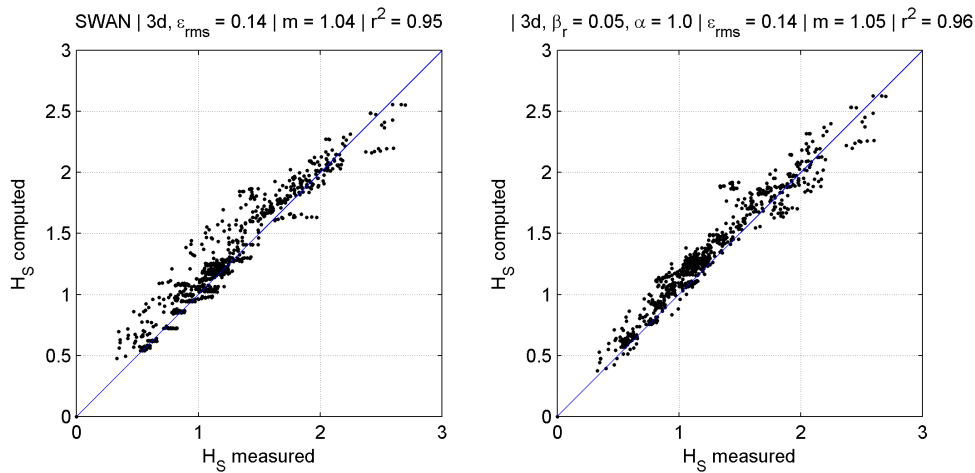


Figure 6.20 Comparison between measured and computed significant wave height for SWAN (left figure) and the roller model (right figure)

The cross-shore distribution of the wave height computed using SWAN and using the roller model is further examined. Figure D.5 and Figure D.6 in Appendix D compare for all cases the computed wave heights per measurement location in the cross-shore. With the linear least-square-fit (m) it can be determined at which locations the roller model and SWAN over- or underestimates the wave height. The m -values for the different cross-shore locations are compared in Table 6.4. The corresponding location numbers are shown in the profile in Figure 6.21. The roller model shows less overestimation of the wave height compared with SWAN for the location close to the shore. However, from $x > 210$ m the wave height computed using SWAN are less overestimated compared with the roller model.

Table 6.4 Linear least-square-fit roller model and SWAN

Locations	Roller model		SWAN	
	m	rms	m	rms
<i>all locations</i>	1.05	0.15	1.04	0.15
1	1.14	0.15	1.37	0.29
2	1.10	0.14	1.29	0.28
3	1.08	0.15	1.12	0.18
8	1.06	0.15	1.03	0.09
9	1.07	0.17	1.06	0.12
10	1.08	0.12	1.02	0.07
4	1.03	0.13	1.03	0.10
11	1.03	0.13	1.02	0.10
12	1.03	0.16	1.03	0.11
13	1.10	0.20	1.10	0.17
5	1.04	0.14	1.03	0.11
6	1.05	0.14	1.03	0.11
15	1.06	0.16	1.02	0.13
14	1.03	0.12	1.00	0.11
16	1.07	0.16	1.02	0.13
17	1.06	0.16	1.02	0.13
19	1.03	0.15	1.00	0.14
18	1.03	0.13	1.00	0.12
20	1.05	0.15	1.02	0.14

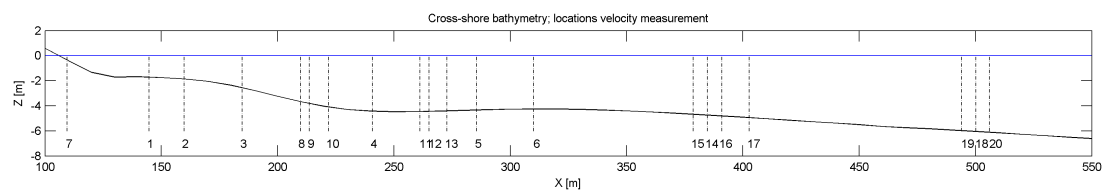


Figure 6.21 Cross-shore location wave height measurements

6.5.3 Comparing results 2DH (Van der Werf)

Van der Werf (2009) determined that for the 2DH approach a Chézy of $60 \text{ m}^{0.5}/\text{s}$, a background eddy viscosity of $0 \text{ m}^2/\text{s}$ and a value for the calibration parameter α of 1 provides accurate results compared with the measurements. Van der Werf furthermore used the default value of the roller slope of 0.10. To compare the performance of the 3D approach with the 2DH approach also a 2DH simulation is made with the abovementioned settings. The results of the 2DH and 3D approach are compared with the 46 cases in Figure 6.22. Although the slope of the linear least-square-fit deviates more from the

value 1 than for the 2DH approach, the root-mean-square error is smaller for the 3D computations. Furthermore, the correlation between the measured and computed longshore currents is higher for the 3D approach than for the 2DH approach.

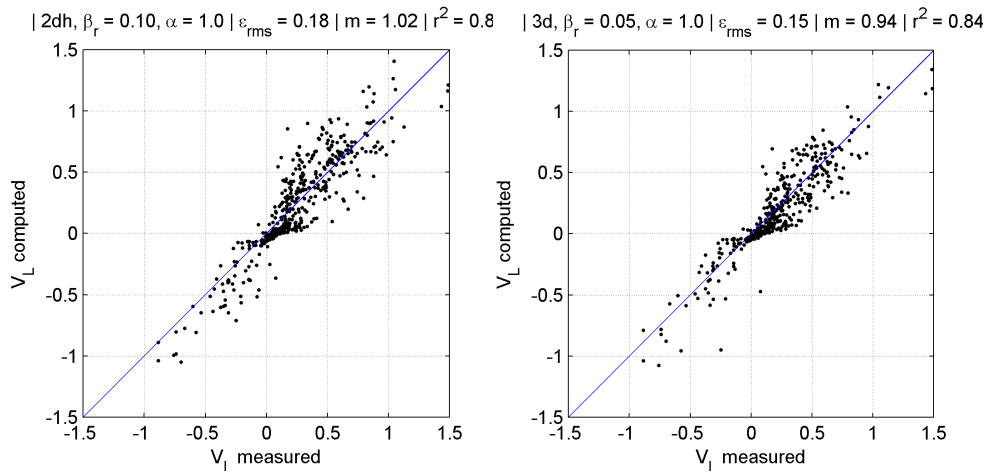


Figure 6.22 Comparison 2DH and 3D approach for all 46 cases

6.5.4 Conclusions

For the calibration the Chézy roughness coefficient, horizontal background eddy viscosity and the roller slope is varied. The best results are obtained using a;

- Chézy value of 60 [$\text{m}^{0.5}/\text{s}$]
- Roller slope of 0.05 [-]
- Background horizontal eddy viscosity of 0 [m^2/s]
- Calibration parameter α of 1

The 3D approach shows a reasonable good prediction of the wave height ($m = 1.06$, rms-error = 0.15 m and $r^2 = 0.96$) and the longshore current ($m = 0.94$, rms-error = 0.15 m and $r^2 = 0.84$). The correlation factor is smaller than 1, which implies that the measured and computed data show some spread compared with the linear least-square-fit. Furthermore, the values of the longshore currents are generally, for the abovementioned Delft3D settings, underestimated. Increasing the roller slope to 0.10 reduces the underestimation but increases the rms-error and decreases the correlation.

The wave height computed by Delft3D using the roller model shows for the 46 cases an general overestimation. Computing the wave heights using SWAN reduces the overestimation of the wave height outside the surf zone. However, near the shore the overestimation increases strongly. The wave energy decay shows better results for the roller model.

The 2DH and 3D computations both show reasonable results compared with the measurements. The rms-error of the 2DH results is higher (0.18 m/s) compared with the 3D results (0.15 m/s). The 3D approach also shows a higher correlation coefficient, which implies that the computed values, in general, correspond well to the slope of the least-square-fit. However, these results do not justify a conclusion concerning which approach (2DH or 3D) is the best. In general, this would be difficult to say since a statistical comparison is difficult, a lot of calibration parameters are available to alter the outcome in such a way that either the linear-least-slope increases, or the correlation coefficient increases or the rms-error reduces. However, the 'best' approach can be further quantified by taking sediment transport and morphology into account. Eventually the goal of knowing the wave-induced

currents inside the surf zone is to determine the amount of sediment transported along a coast and eventually also the change of the coastline.

In the next paragraph the 3D approach is further assessed by looking at the vertical distribution of the longshore currents. Using the 3D approach provides the opportunity to look at the vertical distribution of the longshore current, which is not possible in the 2DH approach.

6.6 Data Thornton and Stanton

6.6.1 Introduction

When using the 3D approach in Delft3D a vertical distribution of the currents is obtained which is important for suspended sediment related transport. In the previous paragraph the performance of the 3D approach is determined by comparing the (approximately) depth-averaged velocity with the measurement obtained at a vertical elevation which corresponds to the location of the depth-averaged velocity (assuming a logarithmic velocity profile).

To determine the performance of the vertical distribution of the current velocity computed using the 3D approach the measurements obtained by Thornton and Stanton are used. Thornton and Stanton measured the velocity using a sled (Figure 6.23) which consists of a stack of 8 electromagnetic flow meters to measure the current velocity.



Figure 6.23 Sled used to collect the current velocity at different vertical elevations (www.frf.usace.army.mil/sandyduck/)

For each location the sled has measured the currents for approximately 1 hour after which the sled is repositioned to a different cross-shore location.

6.6.2 Remarks

The model used in the previous paragraph is again used to compare the computed vertical velocity distribution with the measured distribution. Reniers et al used inverse shoaling and refraction of the wave height measured at the offshore located pressure array ($x = 500$ m), located in the same cross-section as the sled-measurements, to obtain the wave height at the 8 meter depth contour. This is done to avoid errors in the local wave height (i.e. at the location of the sled). At the location of the sled Reniers et al had the exact wave height and therefore the actual forcing of the current. In the current Delft3D model the wave height is determined based on the wave spectrum computed from a time series of the surface elevations of a wave buoy located at the 8 meters depth contour. This makes the current model more sensitive to the measurements and the applied theories. As described in the previous paragraph the computed wave height deviated from the measured wave height; underestimating the wave height offshore while overestimating the wave height closer to the shore.

Therefore a one-on-one comparison with the results obtained by Reniers et al (2004) should be done with care.

The model used by Hsu et al (2008) and Van der Werf et al (2009) a simulation is made for each three hour time span. The measurements obtained by Thornton and Stanton where only done during daylight. The 46 cases, which are elaborated in this chapter are chosen such that the offshore significant wave height exceeds 0.6 meters. Therefore, also cases during the night are chosen. Furthermore, the measurements by Thornton and Stanton started at the 29th of September, reducing the number of available cases by two days. This resulted in just 12 available cases for which a direct comparison was possible. The cases, which are used, are described in Table 6.5.

Table 6.5 Cases used to compare computations with measurements

Date and time	Cases Sandy Duck 1997					
	Z _{tide} (m)	V _{wind} (m/s)	θ _{wind} (°)	H _s (m)	T _p (s)	θ _{wave} (°)
02-Oct-1997 07:00:00	0,92	6,16	43	1,1	5,8	32
02-Oct-1997 10:00:00	0,59	5,15	28	1	6,6	22
02-Oct-1997 13:00:00	-0,15	6,06	359	0,9	6,6	34
11-Oct-1997 07:00:00	-0,06	9,53	22	1,1	4,8	36
11-Oct-1997 10:00:00	-0,01	8,81	30	1,2	5	36
11-Oct-1997 13:00:00	0,69	8,2	15	1,2	5,2	32
15-Oct-1997 13:00:00	-0,27	9,72	348	1	4,8	36
15-Oct-1997 19:00:00	1,13	11,18	352	1,3	5	38
16-Oct-1997 19:00:00	1,14	8,42	34	1,8	6,2	10
18-Oct-1997 10:00:00	1,28	0,92	24	1,8	6,6	16
18-Oct-1997 19:00:00	0,83	11,9	27	2,2	8,2	10
20-Oct-1997 22:00:00	0,87	2,21	274	2	13,6	8

6.6.3 Results

The Delft3D settings used to compare the computed vertical distribution of the longshore current with measurements are those described in the previous paragraph using:

- Chézy value of 60 [m^{0.5}/s]
- roller slope of 0.05 [-]
- background horizontal eddy viscosity of 0 [m²/s]
- calibration parameter α of 1

In this study the root-mean-square error, the slope of the linear least-square-fit and the correlation coefficient is used to quantify the performance of Delft3D. Reniers et al (2004) used a different method to determine the skill of the model. To compare the obtained results in this study with those found by Reniers et al, also the skill according to Reniers et al is determined. This is done according to;

$$skill = 1 - \frac{\sum_{i=1}^n (Y_i - X_i)^2}{\sum_{i=1}^n Y_i^2} \quad (6.4)$$

The vertical distribution of the longshore current velocities is shown in Figure 6.24 for all 12 cases. The dashed horizontal line represents the water depth including water level set up. For some cases the electromagnetic (EMF) located just beneath the water surface shows a result which deviates from the other EMF. Since the vertical elevation of the EMF is fixed, for high waves the EMF might be above the

water surface in the trough of a wave. For statistical comparison the top two EMF are excluded. Figure 6.24 shows that for some cases the velocity distribution shows a reasonable fit but also for some cases a large deviation is found. Figure 6.25 shows the results for all 12 cases. This figure shows that several groups of point exists which are concentrated around each others. These are the individual cases. Furthermore, a general overestimation is found ($m = 1.16$) and a low correlation between the measured and the computed longshore currents ($r^2 = 0.59$). A skill level of 0.59 for all measurements is obtained. This is a low value in comparison with the obtained skill level by Reniers et al (2004); a skill level of approximately 0.85 ~ 0.90 was found. If the cases 97100210 (second figure) and 97101619 (bottom left figure), these are the computations with large deviations, are left out a skill level of 0.65 is obtained. Still this is considerably lower as found by Reniers et al (2004).

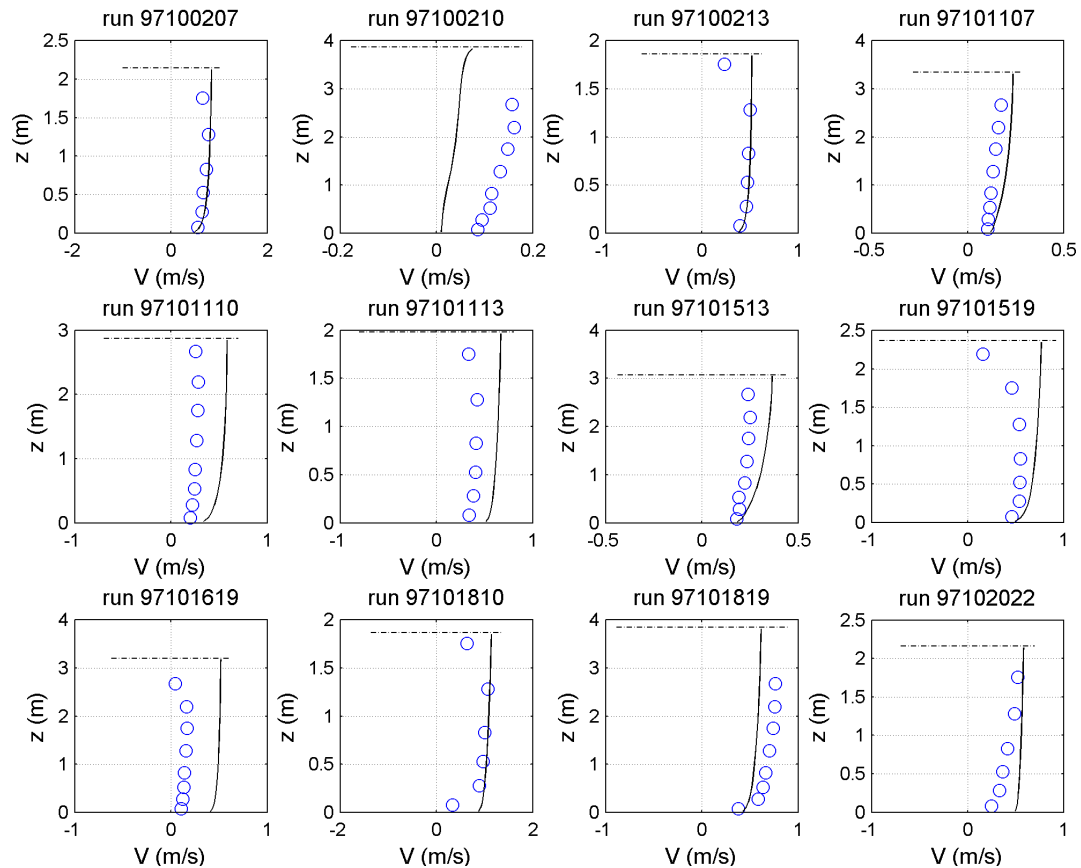


Figure 6.24 Computed vertical distribution of the longshore current velocity (black-line) compared with measurements obtain by Thornton and Stanton (blue circles)

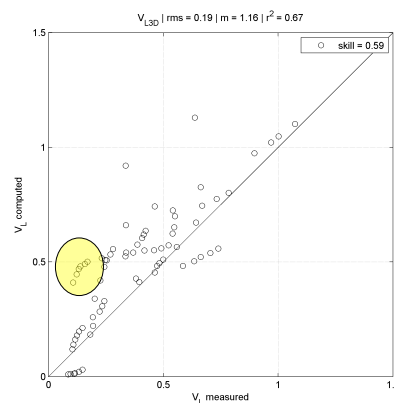


Figure 6.25 Comparison of all 12 cases

6.6.4 Conclusions

These results show that the performance of the vertical distribution of the longshore current is not very high compared with the performance of the depth-averaged velocities obtained by Elgar et al. A correlation coefficient of 0.67, a value for m of 1.16 a rms-error of 0.19 m/s and a skill level of 0.59 are found. The computed vertical distributions in general are overestimated compared with the measurements. A reason for this might be due to the overestimation of the wave height at the location of the measurements. Reniers et al (2004) computed the wave height by inverse refraction and shoaling from the most seaward located measurement location till the 8 meter depth contour. This reduces the error of the wave height computation to a minimum. The used Delft3D model applies a wave spectrum which is derived from a water surface elevation measurement over time. As mentioned in the previous paragraph Delft3D generally overestimates the wave height computation which might result in the abovementioned overestimation of the longshore current.

These results are somewhat biased since if at a specific measuring location the velocity in general is overestimated then the vertical distribution of the current velocity will also be overestimated. Since every point has the same weight this would mean that if this location has a general overestimation the individual point share this overestimation and therefore these results are biased (an example is the yellow circle in Figure 6.25). If we just look at Figure 6.24 and compare the vertical distributions of the longshore current by eye then the computed results do not seem too bad. A general overestimation of the longshore current can be observed but the vertical profiles correspond reasonably well with the measured distribution.

6.7 Conclusion

The performance of the cross-shore and vertical distribution of the longshore current velocity is determined for the measurements obtained during the Sandy Duck 1997 campaign by respectively Elgar et al and Thornton and Stanton. Elgar et al measured the cross-shore distribution of the longshore current and wave heights. These measurements are already used in previous studies (Hse et al, 2008; Van der Werf, 2009; Reniers et al, 2004) to compare with computed results.

In this study it is found that the cross-shore distribution of the longshore currents computed using the 3D approach, with the updated bed shear stress calculations, are in good agreement with measurements. Close to the shore Delft3D overestimates the longshore currents while further seaward the 3D approach underestimates the longshore current. A possible explanation for the offshore underestimation is due to the exclusion of the horizontal tide (tide-induced current) which is typically largest in deeper waters. The cause for the overestimation of the wave height computed by the roller model might be the fact that no dissipation other than wave-breaking is included. Including wave energy dissipation due to bottom friction might increase the accuracy of the wave height computations by the roller model.

The performance of computing the vertical distribution using the current set up of the Delft3D model shows insufficiencies compared to the computations of Reniers et al (2004). Reniers et al (2004) used inverse shoaling and refraction to obtain the correct wave height at the location of the measurements. In the current Delft3D a wave spectrum is applied as wave boundary condition based on a time-series of the surface elevation at the 8 meter depth contour. The skill level obtained in this study deviates significantly from those found by Reniers et al (2004), but could possibly be improved if the same approach for the wave condition is applied as is done by Reniers et al.

7 Conclusions and Recommendations

In this study a hydrodynamic validation of Delft3D is performed, in which primarily the wave-driven longshore current in the surf zone is examined. The main objectives are (i) to determine the driving forces of the currents in the surf zone and how these currents are computed for morphological related topics in Delft3D, (ii) to determine what the differences are between the 2DH and 3D computed longshore currents and what causes the 3D approach to deviate from the 2DH approach. Furthermore, (iii) to determine the performance, of the 2DH and 3D approach in Delft3D, of computing the longshore currents in the surf zone.

This Chapter describes the performed hydrodynamic validation of Delft3D where in paragraph 7.1 the main research objectives are answered and in paragraph 7.2 recommendations for further research is presented. In paragraph 7.3 a closure of this research is described.

7.1 Conclusions

This Chapter presents the conclusions of the research on 3D computations of wave-driven longshore currents in the surf zone. This research first described the general processes inside the surf zone, a brief description of the general theories and approaches nowadays used and a brief introduction into the numerical process-based modelling program Delft3D. After this the difference between the 2DH and 3D approach is described followed by a comparison of 2DH and 3D computations for an idealised case. From this a model improvement is suggested, which is extensively validated using both laboratory and field measurements. The conclusions for the abovementioned objectives are described below.

What are the driving forces of the currents in the surf zone and how are these currents computed for morphological related topics?

Wave-breaking induced forces are the driving force of the longshore current. The process-based numerical modelling program Delft3D computes the longshore currents for morphological purposes. Therefore the currents are computed based on wave-averaged properties of the waves.

Delft3D can compute these currents in several dimensions. In this study the 2DH and 3D approaches are used. The main difference between the 2DH and 3D computations is the inclusion of vertical computational layers to take the vertical flow, the vertical distribution of the horizontal flow and vertical variations of forcing and currents into account. In the 3D approach wave-breaking induced production of turbulence, streaming and Stokes drift are included aiming at a realistic representation of the vertical velocity profile. The main advantage of the 3D approach is that a vertical profile of the current velocity is obtained, which is important for suspended sediment related transport especially in cases where the vertical velocity distribution deviates from a logarithmic distribution.

For the computation of the bed shear stress in the 3D approach, the quadratic friction law is used and a logarithmic vertical distribution of the longshore current is assumed. In the 2DH approach the depth-averaged velocity is used, while in the 3D approach the velocity is the computational layer just above the bed is used.

What are the differences between the 2DH and 3D computed longshore currents and what causes the 3D approach to deviate from the 2DH approach?

The 3D approach underestimates the wave-driven longshore currents compared with the 2DH approach up to a factor 2 for small angles of incident waves. These results are independent on the local wave conditions.

The 3D approach shows a dependency on the thickness of the computational layer just above the bed. Decreasing the thickness of the computational layer just above the bed results in a decrease of the longshore current.

The dependency is due to the assumption of a logarithmic vertical distribution of the longshore current in the computation of the bed shear stress. This assumption is valid for currents that are induced by e.g. a gradient in the water level. However, for wave-induced longshore currents this is no longer valid since wave-breaking induced mixing results in a more vertically uniform distributed longshore current. The assumption of a logarithmic vertical distribution results in a too low (rough) value for the Chézy coefficient compared to the velocity near the bed. Therefore, the bed shear stress is overestimated, which results in a reduction of the longshore current.

The dependency of the 3D approach on the chosen number of vertical layer can be, by using the velocity at an elevation above the bed independent of the computational layer thickness, avoided. The edge wave boundary layer is suggested to use and it is shown that this decreases the dependency on the number of vertical layers applied.

What is the performance, of the 2DH and 3D approach in Delft3D, of computing the longshore currents in the surf zone?

The 3D approach is validated using both laboratory and field measurements. The laboratory tests (Reniers and Battjes, 1997) showed the new method of computing the bed shear stress improved the agreement between the 3D computations and the measurements.

Important calibration parameters are found to be (i) the background horizontal eddy viscosity, (ii) the bottom roughness and (iii) the roller slope.

After calibration both the 2DH and 3D computed longshore currents corresponded well with measurements. However, in the bar trough the wave-driven currents are underestimated.

The wave height computations show an overestimation of the wave height in the bar trough. Since the longshore current is driven by the dissipation of roller energy, the overestimation of the wave height in the bar trough can explain the underestimation of the longshore current in the bar trough. Too little wave energy is dissipated to drive the longshore current.

In Delft3D the longshore current is not determined based on the total radiation stresses but on the roller dissipation induced force. Therefore the water level set down is not taken into account. Including the wave forces results in a larger longshore component of the total force and therefore an overestimation of the longshore current. However, the water level set down and set up is in good agreement with measurement if the forcing is based on the total radiation stress, neglecting the roller force. This is remarkable since theoretically the same outcome is expected.

The possible effect of including the roller induced mass-flux is examined and thought to be small. The roller induced mass-flux is thought not to positively influence the underestimation of the longshore current in the bar trough.

The comparison of the 3D approach with in-situ measurements (at Sandy Duck 1997) showed that for both the 2DH and the 3D approach the computed wave-driven longshore currents in the surf zone correspond reasonable well with measurements. For the 2DH approach an rms-error of 0.18 m/s, a

linear least-square-fit of 1.02 and a correlation coefficient of 0.8 are found. For the 3D approach an rms-error 0.15 m/s, a linear least-square-fit of 0.94 and a correlation coefficient of 0.84 are found.

In case of the field experiments the longshore currents close to the shore are generally overestimated. This is generally also the case for the wave height. The amount of wave energy dissipation, thus also the amount of roller dissipation, which drives the longshore current, is too large close to the shore.

In the surf zone, where the prediction of the wave height is important for the longshore current, the roller model overestimates the wave height. A reason for the overestimation could be the fact that no other source term but wave-breaking is included in the wave energy balance equation in the roller model. Therefore, the dissipation of wave energy due to bottom friction and white-capping (important for deeper water) are not included.

The SWAN computed wave heights show better results for the wave height computed outside the surf zone. Both the slope of the linear least-square-fit and the root-mean-square wave height show better results for SWAN than for the roller model. However, in the surf zone SWAN significantly underestimates the decay of wave energy resulting in too little dissipation of wave energy compared with the measurements.

7.2 Recommendations

Delft3D setting related recommendations are:

- Determining the bed shear stress using the velocity in the layer just above the wave boundary layer is suggested to be implemented in the standard Delft3D. This is a work-around solution for the problem and has shown to provide valid results for both laboratory and field measurements.
- The most important calibration factors are the bottom roughness, horizontal background eddy viscosity and the roller slope for which the default settings, in case of wave-driven longshore currents for sandy coasts (e.g. as found at Sandy Duck, NC, USA and Egmond, The Netherlands), should be $60 \text{ m}^{0.5}/\text{s}$, $0 \text{ m}^2/\text{s}$ and 0.05 (-) respectively.
- Increasing the number vertical layers beyond 15 layers show little differences. Using only 5 numbers shows irregularities. For practical purposes and reducing the computational time a number of 8 – 10 vertical layers can be applied. However, if an accurate vertical distribution of the wave-induced longshore current is necessary (e.g. suspended sediment transport related problems) and the computational time is not very important (e.g. small model area) 15 layers are suggested to use applying a log-log distribution and a variation factor of 1.4 between thickness of subsequent layers. A minimum thickness of approximately 2 % of the water depth is recommended.
- The value for γ according to Ruessink et al (2003) should be the default setting in Delft3D.
- The default setting for streaming in Delft3D should be 0.1. This provides the best results compared with measurements.

General recommendations are:

- The wave forces in the roller model should be included in Delft3D since these forces are physically realistic. The discrepancy found in this study between the default Delft3D

translation of wave-forces to a current and using the total radiation stress induced force should be a topic of further research.

- The translation of waves approaching a coast and the resulting currents in the surf zone should be further research. This could be done using the inverse modelling techniques on laboratory measurements where accurate and with a high cross-shore resolution measurements are performed.
- Additional source terms, wave energy dissipation due to white-capping and bottom friction, should be implemented in the roller model to more accurately predict the wave height. The roller model should then be further subjected to a validation study to determine the performance of the wave height computations.
- To determine if the processes, added in the 3D approach to simulate a realistic vertical distribution of the current velocity, provide an accurate vertical distribution of the longshore and possibly also the cross-shore current, an approach as performed by Reniers et al (2004) is recommended. Only if the forcing are exactly right at the location of the measurement, the contribution of these processes can be verified.
- In this study only the 3D wave-induced longshore currents are validated. Further research should be carried out to determine if the same unrealistic morphology as was found in Walstra et al (2008) is also computed using the new approach of computing the bed shear stress. Therefore, the focus of further validation research of the new approach of computing the bed shear stress should be shifted to the transport of sediment and coastal morphology.
- Although the effect of the new method on sediment transport and morphology is not yet determined, still a 3D approach is recommended for wave-induced sediment transport related problems since the assumed logarithmic vertical distribution of the current velocity is not valid. This is especially the case for the cross-shore currents but also for the longshore current.
- The 3D approach by assuming hydrostatic pressure is actually an extended 2DH approach. No vertical momentum equation is solved; the vertical current velocity is computed from the continuity equation. The effect of the hydrostatic pressure assumption should be further researched by comparing it with a non-hydrostatic model with the same underlying concept. It is recommended to use the Reniers and Battjes laboratory tests to examine the effect of non-hydrostatic pressure.

7.3 Closure

This paragraph is added to discuss the application of process-based modelling for practical purposes and the choices made during this study.

Delft3D is a tool to amongst other things compute the morphodynamics of a coast based on physical processes. However, computing coastal morphodynamics requires a lot of information. The wave-induced currents along the coast are dependent on an accurate wave height computation, which is in case of wind waves, which are not deterministic (in contrast to tidal waves), is already difficult to compute. Errors in the wave height computations lead to unavoidable errors in the flow velocities. Since sediment transport is dependent on the local currents, errors in the flow prediction are amplified for the sediment transport. This continues until the morphodynamics are computed. This emphasizes the importance of accurately computing the wave conditions and the corresponding hydrodynamics since a lot of uncertainties are present.

Within Delft3D still a lot of assumptions are presents and some processes are described schematically. Taking into account the fact that Delft3D is often used for an engineering tool to qualify and quantify the effect of certain hydraulic engineering projects, the future development of the Delft3D model should be solely based on describing the processes how they are and reducing the amount of tuneable or empirical parameters. Although reducing the assumptions (e.g. hydrostatic pressure) lead to an unavoidable increase in computational time and therefore the model becomes more expensive, still having a tool for which little calibration is necessary and the results correspond well with the measurements is more valuable.

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A Delft3D

A.1 Introduction

This Appendix explains the process-based coastal area model Delft3D developed by former WL | DelftHydraulics, at present Deltares. With Delft3D it is possible to make 1D, 2D horizontal averaged, 2D depth-averaged and 3D calculations. Recently also a quasi-3D version is implemented in Delft3D (Henrotte, 2008). Delft3D has a wide application range and can make prediction of hydrodynamics, morphodynamics but also ecology, pollution spreading, etc.

The Delft3D model consists of several modules to represent different physical processes. Physical processes that are included are; currents, waves, sediment transport and bottom changes. During the first stage of this study only the hydrodynamics are taken into account, which are represented in the flow and wave module.

In the following paragraphs the theoretical background of the modules used in this study and how they are implemented are explained.

A.2 Delft3D – Flow

A.2.1 Numerical background

Delft3D is based on finite differences and therefore the shallow water equations have to be discretized. In Delft3D – Flow a staggered grid is applied which means that not all quantities are defined at the same location in the numerical grid. Figure B.1 shows an example of a staggered grid used in Delft3D. Water levels are calculated at a different location in the grid than for instance the flow velocity.

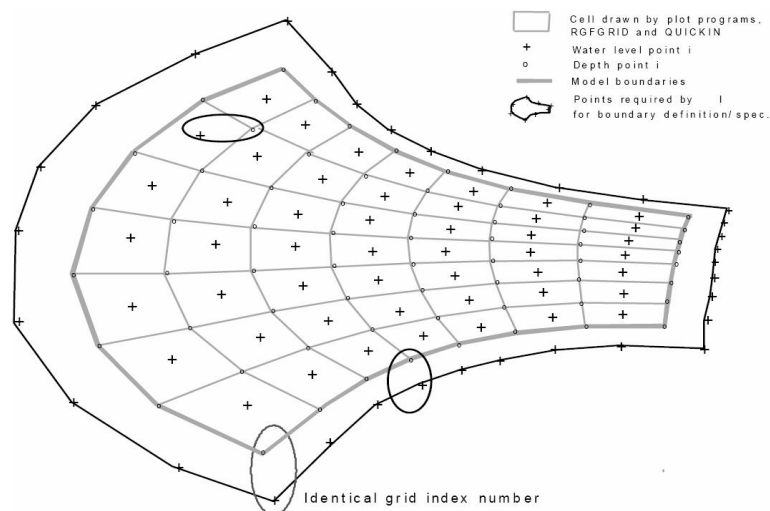


Figure B.1 Staggered grid in Delft3D

The advantages of using staggered grids are the implementation of boundary conditions, the smaller number of discrete state variables needed to obtain the same accuracy as non-staggered grids and for shallow water solvers it prevents spatial oscillations in the water levels (Stelling, 1984).

Delft3D uses the Altering Direction Implicit (ADI) method for solving shallow water equations. The ADI method splits one time step into two stages, half a time step long, and both are solved in a

consistent way with at least second order accuracy. This method was extended with a special approach for the horizontal terms and resulted in a scheme denoted as a 'cyclic method' (Stelling and Leendertse, 1991).

Using an explicit time integration of the shallow water equations on a rectangular grid should satisfy a time step condition based on the Courant number for wave propagation. To obtain sufficient accuracy the Courant number has to be below a set threshold value. The Courant number for two dimensional models is defined as (Stelling, 1984):

$$Cr_{wave} = 2\Delta t \sqrt{gH} \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}} < 1 \quad (A.1)$$

Where Cr is the Courant number is, Δt the time step, g the gravitational acceleration, H the total, local water depth, Δx and Δy the grid size in x- and y-direction respectively.

A.3 Delft3D – Wave (SWAN)

A.3.1 Introduction

Delft3D-Wave module is used to compute the evolution of wind-generated waves in coastal waters (e.g. estuaries, tidal inlets, etc.). The Wave module computes wave propagation, wave generation by wind, non-linear wave-wave interactions and dissipation for deep, intermediate and finite water depths.

Presently two wave models are implemented in Delft3D, the second-generation HISWA wave model (Holthuijsen et al., 1989) and the third-generation SWAN wave module (Holthuijsen et al., 1993). In this study the SWAN wave module is used and therefore this model will be further described in this paragraph.

A.3.2 SWAN wave model – physical background

SWAN, which is an acronym for **S**imulating **W**aves **N**earshore, is based on the discrete spectral action balance equation and is fully spectral in all directions and frequencies. This implies that short-crested random wave fields that propagate simultaneously from all directions can be computed. Therefore e.g. swell can be super-imposed on a wind sea generated at a certain location (Deltares, 2007b). Furthermore, SWAN takes propagation due to current and depth (including refraction), wave generation by wind, dissipation due to whitecapping, bottom friction and depth-induced wave breaking and non-linear wave-wave interactions into account.

The spectral action balance equation is used instead of the energy density spectrum since in the presence of currents the action density is conserved while the energy density is not. The energy density divided by the relative frequency is equal to the action density:

$$N(\sigma, \theta) = \frac{E(\sigma, \theta)}{\sigma} \quad (A.2)$$

In Cartesian co-ordinates the spectral action balance equation reads:

$$\frac{\partial N(\sigma, \theta)}{\partial t} + \frac{\partial c_x N(\sigma, \theta)}{\partial x} + \frac{\partial c_y N(\sigma, \theta)}{\partial y} + \frac{\partial c_\sigma N(\sigma, \theta)}{\partial \sigma} + \frac{\partial c_\theta N(\sigma, \theta)}{\partial \theta} = \frac{S(\sigma, \theta)}{\sigma} \quad (A.3)$$

In which:

$N = N(\sigma, \theta, x, y, t)$	Action density
$S = S(\sigma, \theta, x, y, t)$	Source term
σ	Relative frequency
c	Propagation velocity

First term:	Local rate of change of action density in time
Second term:	Propagation of action in x-direction
Third term:	Propagation of action in y-direction
Fourth term:	Shifting of the relative frequency due to variations in depths and currents
Fifth term:	Depth and current induced refraction
Sixth term:	Source term (generation, dissipation and non-linear wave-wave interactions)

The source term $S(\sigma, \theta)$ represents the effects of generation, dissipation and non-linear wave-wave interactions. Therefore the source term can be divided into three terms:

$$S(\sigma, \theta) = S_{in}(\sigma, \theta) + S_{nl}(\sigma, \theta) + S_{ds}(\sigma, \theta) \quad (\text{A.4})$$

S_{in} = Generation by wind

S_{nl} = Non-linear triad (S_{nl3}) and quadruplet (S_{nl4}) wave-wave interaction

S_{ds} = Dissipation by white-capping ($S_{ds,w}$), bottom friction ($S_{ds,b}$) and depth-induced breaking ($S_{ds,br}$)

In this study the roller model according to and for the reasons as mentioned in (Nairn et al., 1990) is used. The roller model computes the wave energy using the wave energy balance equation. For more details see Appendix 0. Since the roller model is used to determine the forcing the SWAN Wave-module only is used to determine the wave direction and wave length. This is used as input for the roller model.

B Roller model

B.1 Introduction

The roller mode l is implemented in Delft3D to give a more realistic forcing by the waves. The roller model theory is developed since computing the longshore currents based on the radiation stresses resulted in the maximum of the longshore current to be too far offshore (REF!!). The transition zone is the zone where rapid wave decay is observed without an associated increase in energy dissipation. This implies that the release of wave energy takes place further shoreward. (Svendsen, 1984) suggested that a large amount of the wave energy lost in the transition zone is converted to forward momentum flux which occurs primarily inside the surface roller. An extensive review of the theoretical background of the roller model is given in the papers of (Svendsen, 1984) and (Nairn et al., 1990). Here only briefly the applied formulations and assumptions are described.

B.2 Basic formulation

The energy balance equation for organised wave energy reads:

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x}(Ec_g \cos(\alpha)) + \frac{\partial}{\partial y}(Ec_g \sin(\alpha)) = -D_w \quad (\text{A.5})$$

The wave energy is transported with the velocity of the wave groups. For the dissipation of wave energy dissipation (D_w) the formulation of (Roelvink, 1993) is used in Delft3D. The dissipation of organised wave energy is used as source term in the energy balance equation for the roller energy:

$$\frac{\partial E_r}{\partial t} + \frac{\partial}{\partial x}(2E_r c \cos(\alpha)) + \frac{\partial}{\partial y}(2E_r c \sin(\alpha)) = D_w - D_r \quad (\text{A.6})$$

The roller energy is transported at a velocity equal to the wave celerity (C) and dissipated at a rate equal to the roller dissipation (D_r). The formulation of the energy balance equation for the roller energy has the same form as the energy balance equation of the organised wave energy; however in the equation for the roller energy a factor 2 is included. (Deigaard, 1993) discussed this additional factor as the result of volume change of the roller in the wave propagation direction. There is a net transfer of water from the wave to the roller as the volume of the roller increases. This implies an additional momentum exchange occurs between the roller and the underlying wave which results in an additional factor 2. The kinetic energy in the roller in equation (A.6) represents the amount of kinetic energy in the roller according to:

$$E_r = \rho \frac{Ac^2}{2L} \quad (\text{A.7})$$

In which A is the roller surface area and L the roller length which is schematically represented in Figure B.1. The roller energy dissipation is dependent on the shear stress induced by the roller on the surface of the underlying wave.

$$D_r = \tau_r c = \beta \rho g \frac{A}{L} = 2\beta g \frac{E_r}{c} \quad (\text{A.8})$$

In which, τ_r is the roller induced shear stress, c the wave celerity, A the surface area of the roller, L the length of the roller and β the angle of the roller slope as is schematically presented in Figure B.1.

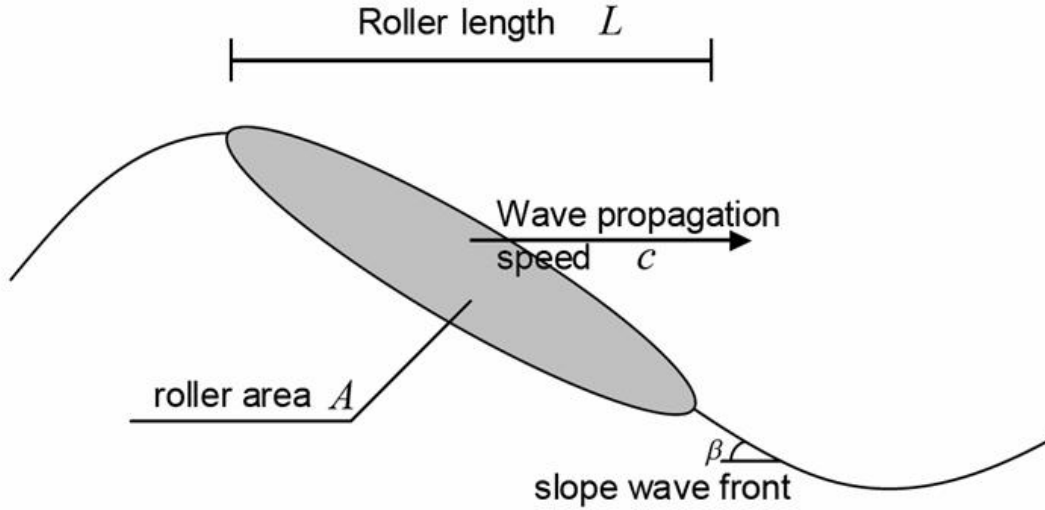


Figure B.1 The concept of a roller travelling on top of a wave

B.3 Implementation Delft3D

Because of the time- and space-varying wave and roller energy a variation in the radiation stresses occurs. This variation results in a force acting on a water body and is responsible for generating currents and a change in water level. In Delft3D this is implemented according to (for a more detail description see Deltares (2007a)):

$$\begin{aligned} S_{xx} &= \left(\frac{c_g}{c} (1 + \cos^2(\alpha)) - \frac{1}{2} \right) E + 2 \cos^2(\alpha) E_r \\ S_{xy} &= S_{yx} = \sin(\alpha) \cos(\alpha) \left(\frac{c_g}{c} E + 2E_r \right) \\ S_{yy} &= \left(\frac{c_g}{c} (1 + \sin^2(\alpha)) - \frac{1}{2} \right) E + 2 \sin^2(\alpha) E_r \end{aligned} \quad (\text{A.9})$$

In which S represents the different tensors of the radiation stress and α the wave angle. This formulation is in great deal the same as in equation (2.14), however now the organized wave energy is divided in a part of the energy in the roller and in the wave. Gradients in these radiation stresses cause a force to be exerted on a body of water. The radiation stresses are divided into a depth-invariant part and a surface stress. Since in Delft3D the roller model is applied to delay the transfer of organised wave energy to the current, the surface shear stress induced by the roller is the only surface shear stress. This stress only takes place if the roller energy is dissipating. This is implemented as:

$$\begin{aligned}
 F_{x,r} &= \frac{D_r}{c} \cos(\alpha) \\
 F_{y,r} &= \frac{D_r}{c} \sin(\alpha)
 \end{aligned}
 \tag{A.10}$$

In which F_r is the vector of the surface stress induced by the roller dissipation while the depth-invariant part reads (the total radiation stress minus the surface stress):

$$\begin{aligned}
 F_{w,x} &= - \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) - F_{x,r} \\
 F_{w,y} &= - \left(\frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right) - F_{y,r}
 \end{aligned}
 \tag{A.11}$$

In which F_w is the vector of the depth-invariant part of the radiation stress. These forces are used as input in the momentum equation.

C Inverse modelling

C.1 Introduction

An integral approach, as suggested by Walstra et al (1996), makes use of a coupling between the extended wave energy and momentum balance equation to deduct the roller properties based on wave height and set up measurements. The inverse modelled forces theoretically should lead to the measured longshore currents if the translation of wave forces to a flow of the water is executed properly. This exercise is performed to validate if the proper translation of wave forces to a flow of the water is applied.

In the next paragraph the principle of the inverse modelling technique is described. In paragraph C.3 the results of the inverse modelling techniques is used as input in Delft3D.

C.2 Inverse modelling approach

In this paragraph the principle of inverse modelling is briefly described. For an extensive description of this technique see Walstra et al (1996).

Assuming that breaking waves are modelled as bores travelling toward the coast with the wave celerity, (Nairn et al., 1990), proposed the following equation for the energy balance:

$$\frac{\partial E_w c_g}{\partial x} + \frac{\partial E_r c}{\partial x} + \tau_s c = 0 \quad (\text{A.12})$$

Where E_w is the kinetic wave energy, E_r is the kinetic roller energy and τ_s the shear stress in the near surface. Deigaard and Fredsøe (1989) suggested that the dissipation is the result of the roller acting as shear stress on the fluid of the wave below ($D_r = \tau_s c = \beta \rho g \frac{A}{T}$). Incorporating the roller contribution in the momentum equation, the time averaged momentum equation then reads:

$$\left(2 \frac{c_g}{c} - \frac{1}{2} \right) \frac{\partial E_w}{\partial x} + M_r + \rho g h \frac{\partial \eta}{\partial x} = 0 \quad (\text{A.13})$$

In which, M_r is the time averaged gradient of momentum in the roller and can be written as:

$$M_r = 2 \frac{\partial E_r}{\partial x} \quad (\text{A.14})$$

The initial step (see Figure C.1) in inverse modelling is to acquire the time-averaged gradient of the momentum in the roller (M_r) using the wave height and set up, which are known from measurements.

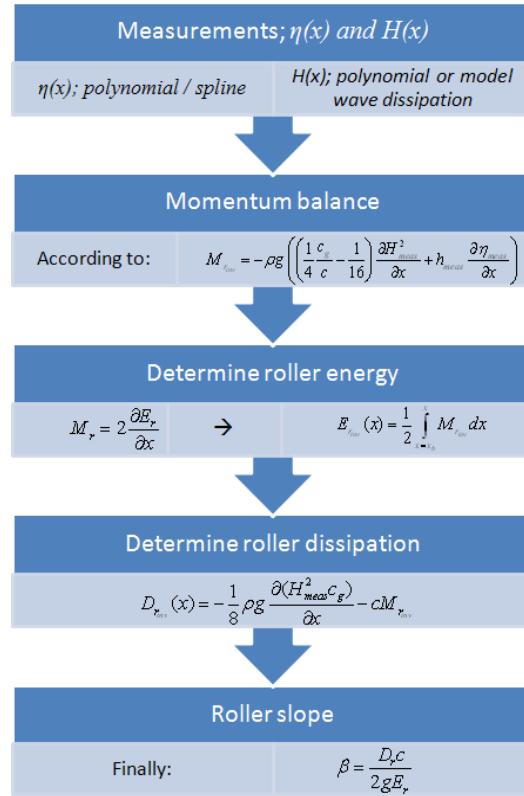


Figure C.1 Flow chart of inverse modelling approach

This is done by rewriting the momentum equation according to:

$$M_{r_{inv}} = -\rho g \left(\left(\frac{1}{4} \frac{c_g}{c} - \frac{1}{16} \right) \frac{\partial H_{meas}^2}{\partial x} + h_{meas} \frac{\partial \eta_{meas}}{\partial x} \right) \quad (\text{A.15})$$

By integrating equation (A.14) the roller energy can be acquired:

$$E_{r_{inv}}(x) = \frac{1}{2} \int_{x=x_b}^x M_{r_{inv}} dx + E_{r_{inv}}(x=x_b) \quad (\text{A.16})$$

The second term on the right hand side is by definition zero since no roller energy is present outside the surf zone. The dissipation of roller energy can be calculated from the energy balance equation in which the cross-shore gradient in the roller energy now represented by the term $M_{r_{inv}}$:

$$D_{r_{inv}}(x) = -\frac{1}{8} \rho g \frac{\partial (H_{meas}^2 c_g)}{\partial x} - c M_{r_{inv}} \quad (\text{A.17})$$

The cross-shore variation of the wave celerity (c) is hereby assumed to be small compared to those of $E_{r_{inv}}$.

The roller dissipation is determined directly from the momentum equation with the assumption that equation (A.14) is the connection between the momentum and energy balance equation (Walstra et al.,

1996). Finally, since both the roller energy and the roller dissipation are known the angle of the roller can be determined according to the approach of Svendsen (1984):

$$\beta = \frac{D_r c}{2gE_r} \quad (\text{A.18})$$

Walstra et al performed an extensive statistical analysis of wave-flume experiments, which resulted in a cross-shore varying expression for the roller slope according to:

$$\beta = 0.1kh \frac{h-H}{H} \cap < 0.1 \quad (\text{A.19})$$

A similar expression to this one is implemented in Delft3D. This expressions has the form of:

$$\beta = 0.025 \frac{1}{kh} \left(\frac{h - H_{rms}}{H_{rms}} \right)^2 \quad (\text{A.20})$$

C.3 Inverse modelling result as input in Delft3D

Based on the measured variation in the water level and the measured wave height the forcing is inversed modelled. The inversed modelled forcing should theoretically result in the measured velocity, assuming that the translation of the forcing to a flow is correctly modelled in Delft3D. Therefore, a simulation is made in which the inverse modelled forces are used as direct input in Delft3D. This would theoretically lead to the observed longshore currents if the implemented translation of wave-induced forces to a current is valid. The roller force computed using inverse modelling techniques is very low compared with the roller forces computed using Delft3D. In the inverse model the roller force is determined as the force extra needed to push the water level to the measured heights. In first instance the water level is forced by the wave forces deducted from the wave height measurements. If the roller forces would only be used as input in Delft3D the longshore current would be computed far too low since the wave force is not taken into account. Therefore both the wave force and the roller force is used as input in Delft3D. Therefore a computation is made in Delft3D including the wave forces according to equation (5.7).

In Figure C.2 the results of the simulation is shown. The black-line shows the Delft3D computations using the default settings after calibration. The red-line shows the results using the inverse modelled forces as input in Delft3D. First, the water level computed with the inverse modelled forcing shows deviating results compared with the measurements. This is remarkable since one would expect these to be on top of each other since the forcing is determined by the measurements. Therefore the measurements should be reproduced in Delft3D with the applied forcing. However, as already mentioned the inverse modelling results are very sensitive for the measurements since the forcing is determine by the cross-shore gradients of the measured water level and wave heights. These gradients are determined from a polynomial which is drawn through the measurements. As can be seen the polynomial makes a fit through the measurements. Therefore assuming values in between the measurements which are not always likely. The water level set-down is for instance overestimated by the polynomial. Therefore the force in x -direction might become too large to compensate for the overestimated set down and achieve the measured set up. This might cause the y -directed force to also be overestimated resulting in the observed overestimated longshore current velocity.

Based on the current measurements it is difficult to argue if the current translation of wave forces to a flow is valid. For a proper comparison with the inverse modelling technique more cross-shore data is needed to compute a accurate cross-shore distribution of the water level set up and set down. If there are enough cross-shore measurement location and these measurements are performed accurately, only then the inverse modelling technique can be applied with the purpose of determining if the current translation of waves to a current is valid.

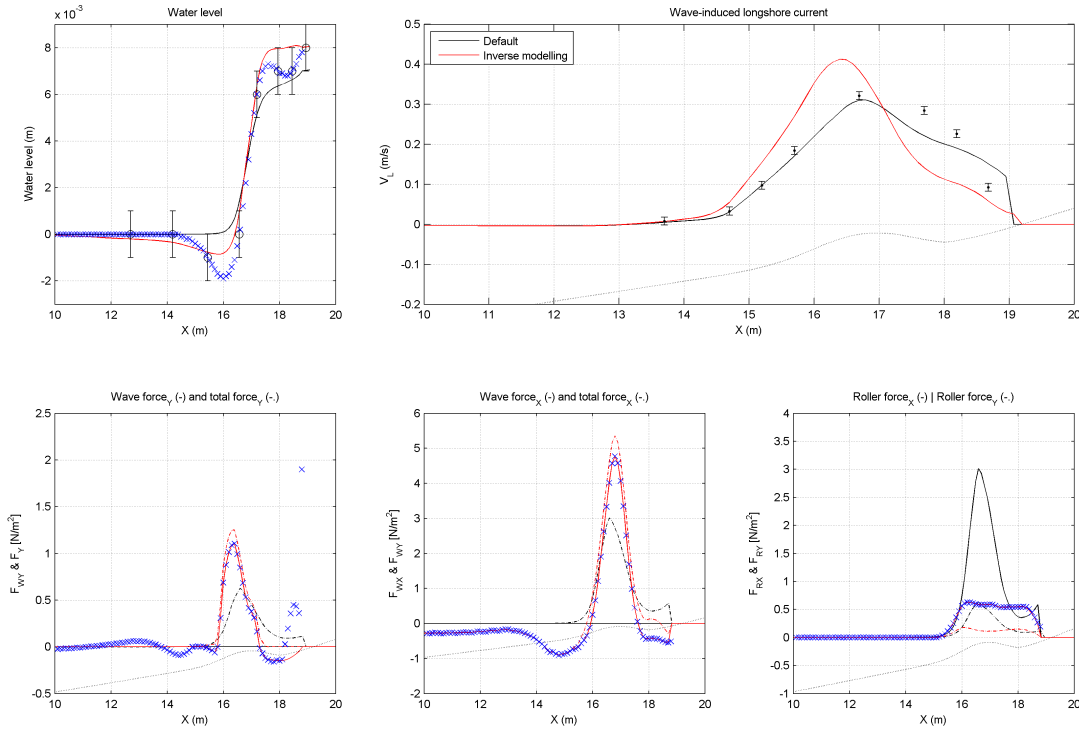


Figure C.2 Results using inversed modelled roller energy dissipation as input (red-line) compared to the computation including all forces

C.4 Conclusion

With the inverse modelling technique insight is gained in the properties of the roller and with that the forcing corresponding to the measured water level and wave height. However, inverse modelling is very sensitive to the measurements since the roller properties are determined based on the cross-shore variations of the water level and the wave height. This is determined by drawing a polynomial through the measurements. Because of the sensitivity to the accuracy of the measurements it is impossible to argue if the current translation of wave forcing to a current is valid. Only if accurate measurements are available the inverse modelling technique can be applied to quantify the translation of wave forcing to a current.

D Validation Duck

D.1 Cases SandyDuck 1997

Date and time	Cases Sandy Duck 1997					
	Z_{tide} (m)	V_{wind} (m/s)	θ_{wind} (°)	H_s (m)	T_p (s)	θ_{wave} (°)
27-Sep-1997 19:00:00	0,64	10,68	71	1,4	5	4
27-Sep-1997 22:00:00	0,06	11,82	79	1,7	6,2	-14
28-Sep-1997 01:00:00	0,24	12,49	77	1,8	6,6	-8
28-Sep-1997 04:00:00	0,81	3,35	101	1,6	7,6	-4
28-Sep-1997 07:00:00	0,64	5,76	195	1,3	7	-2
28-Sep-1997 10:00:00	0,08	5,89	147	1,1	7	-6
28-Sep-1997 13:00:00	0,23	8,34	202	1,1	6,6	10
28-Sep-1997 16:00:00	0,78	7,58	209	1,1	7	6
28-Sep-1997 19:00:00	0,79	5,31	204	1	7,6	-36
02-Oct-1997 01:00:00	-0,2	11,14	17	1,5	5,8	24
02-Oct-1997 04:00:00	0,28	8,65	17	1,4	6,6	22
02-Oct-1997 07:00:00	0,92	6,16	43	1,1	5,8	32
02-Oct-1997 10:00:00	0,59	5,15	28	1	6,6	22
02-Oct-1997 13:00:00	-0,15	6,06	359	0,9	6,6	34
02-Oct-1997 16:00:00	0,04	5,67	26	0,8	6,6	16
02-Oct-1997 19:00:00	0,66	3,94	44	0,6	6,2	30
02-Oct-1997 22:00:00	0,41	1,93	96	0,6	7	18
03-Oct-1997 01:00:00	-0,29	1,02	21	0,6	6,6	12
11-Oct-1997 07:00:00	-0,06	9,53	22	1,1	4,8	36
11-Oct-1997 10:00:00	-0,01	8,81	30	1,2	5	36
11-Oct-1997 13:00:00	0,69	8,2	15	1,2	5,2	32
11-Oct-1997 16:00:00	0,82	8,4	21	1,3	5,8	20
11-Oct-1997 19:00:00	0,15	7,4	40	1,2	5,8	30
11-Oct-1997 22:00:00	-0,11	6,07	46	1,2	10,7	-10
12-Oct-1997 01:00:00	0,49	5,07	48	1,2	10,7	12
15-Oct-1997 10:00:00	0,21	7,72	354	0,9	10,7	-16
15-Oct-1997 13:00:00	-0,27	9,72	348	1	4,8	36
15-Oct-1997 16:00:00	0,62	9,88	345	1,2	5	34
15-Oct-1997 19:00:00	1,13	11,18	352	1,3	5	38
15-Oct-1997 22:00:00	0,37	9,26	6	1,3	5,2	40
16-Oct-1997 01:00:00	-0,25	7,21	360	1,2	5,2	42
16-Oct-1997 04:00:00	0,56	7,21	324	1,2	10,7	-20
16-Oct-1997 19:00:00	1,14	8,42	34	1,8	6,2	10
16-Oct-1997 22:00:00	0,71	9,47	27	1,8	6,2	10
18-Oct-1997 10:00:00	1,28	0,92	24	1,8	6,6	16
18-Oct-1997 13:00:00	0,32	1,88	26	2,2	7,6	12
18-Oct-1997 19:00:00	0,83	11,9	27	2,2	8,2	10
18-Oct-1997 22:00:00	1,08	12,08	15	2,1	8,2	12
19-Oct-1997 01:00:00	0,42	11,37	21	1,9	7	10
19-Oct-1997 04:00:00	0,15	13,1	20	2,1	6,6	12
19-Oct-1997 07:00:00	1,01	13,8	14	2,5	7,6	18
19-Oct-1997 10:00:00	1,53	15,14	13	2,7	7,6	20
19-Oct-1997 22:00:00	1,18	10,22	323	2,6	10,7	12
20-Oct-1997 10:00:00	1,23	10,07	328	2,2	13,6	-6
20-Oct-1997 13:00:00	0,85	9,71	328	2	13,6	-4
20-Oct-1997 22:00:00	0,87	2,21	274	2	13,6	8

D.2 Streaming

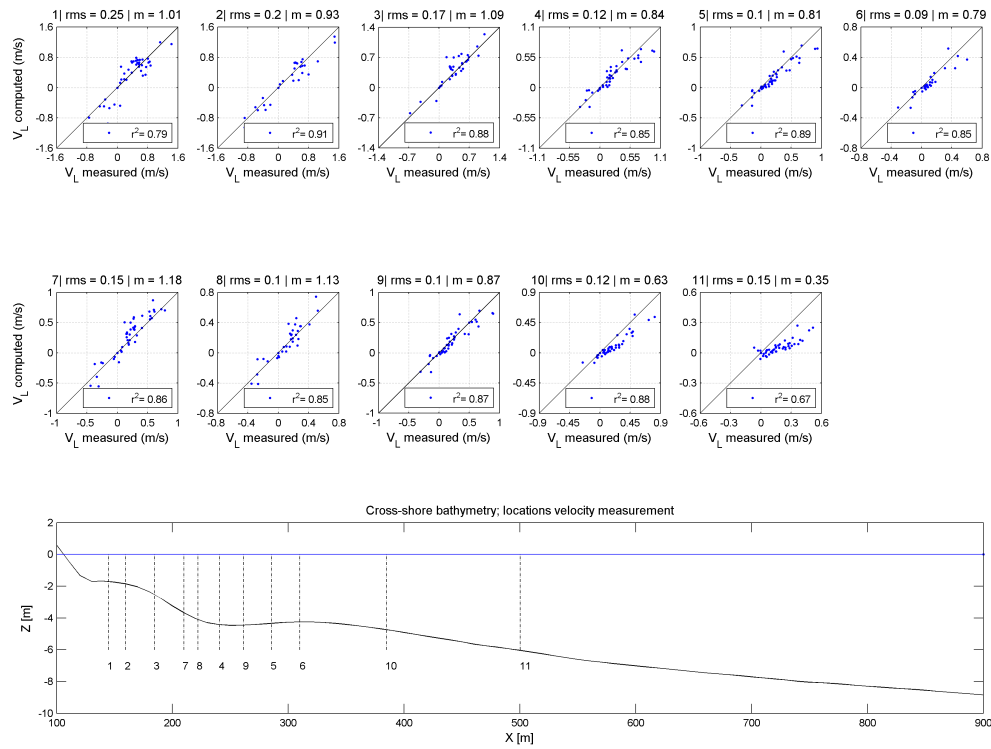


Figure D.1 For $Fwfac$ is 0.5; rms-error for different measurement locations

D.3 Angle of roller

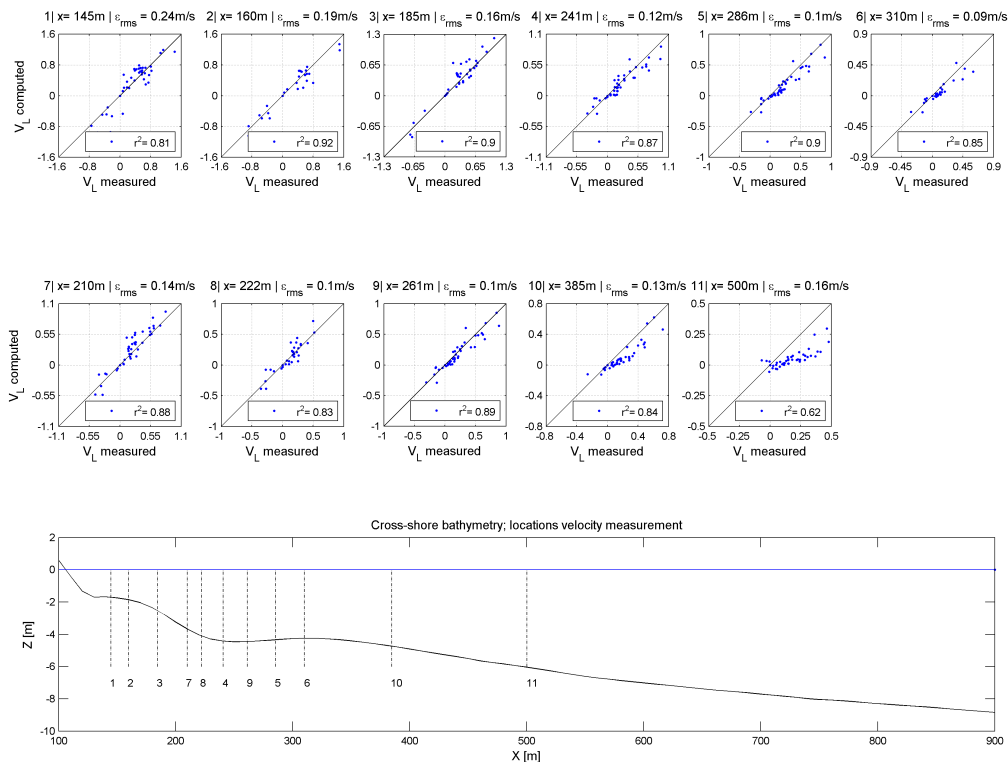


Figure D.2 For β_r is 0.05; rms-error for different measurement locations

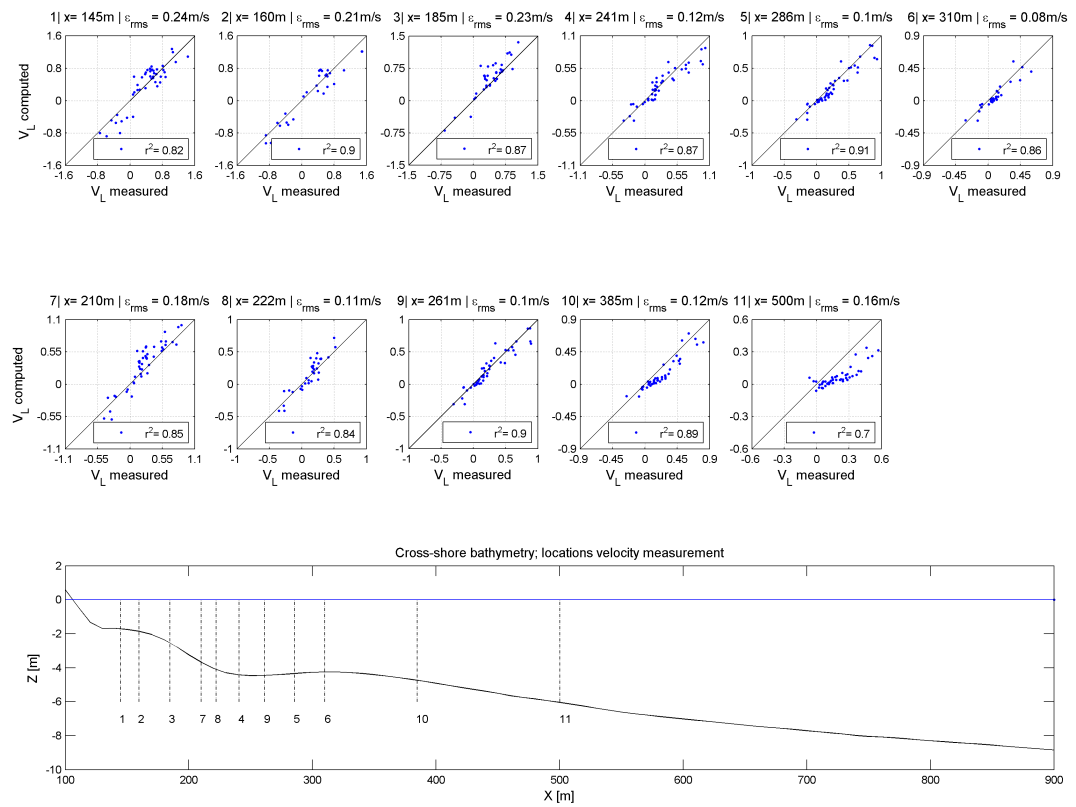


Figure D.3 For β_r is 0.10; rms-error for different measurement locations

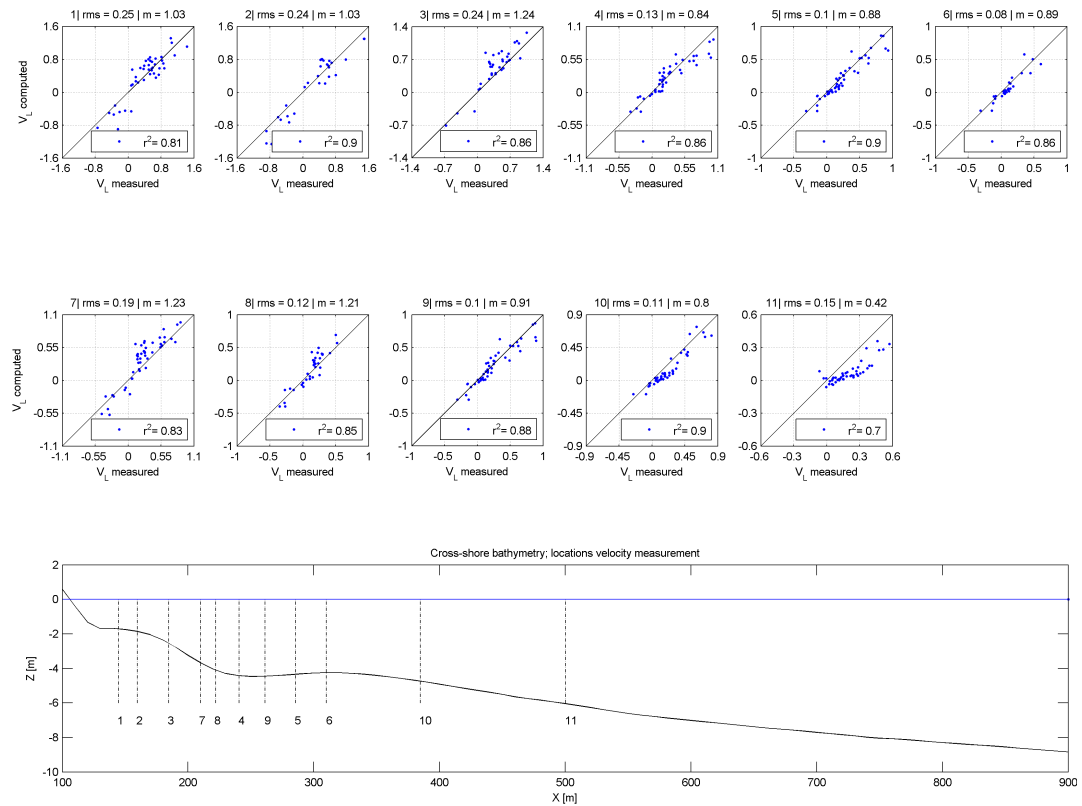


Figure D.4 For β_r is -1 (Walstra et al, 1996); rms-error for different measurement locations

D.4 Calibration factor (α)

Locations	V_L $\alpha = 1.0$			V_L $\alpha = 1.2$			V_L $\alpha = 1.5$		
	ϵ_{rms}	m	r^2	ϵ_{rms}	m	r^2	ϵ_{rms}	m	r^2
<i>all locations</i>	<i>0.15</i>	<i>0.94</i>	<i>0.84</i>	<i>0.15</i>	<i>0.94</i>	<i>0.83</i>	<i>0.15</i>	<i>0.96</i>	<i>0.84</i>
1 (x=145)	0.24	1.03	0.81	0.24	1.02	0.82	0.25	1.05	0.79
2 (x=160)	0.19	0.94	0.92	0.21	0.93	0.90	0.20	0.94	0.91
3 (x=185)	0.16	1.11	0.90	0.23	1.13	0.87	0.18	1.15	0.87
7 (x=210)	0.14	1.17	0.88	0.18	1.16	0.85	0.15	1.20	0.86
8 (x=222)	0.10	1.05	0.83	0.11	1.10	0.84	0.11	1.15	0.82
4 (x=241)	0.12	0.83	0.87	0.12	0.84	0.87	0.12	0.86	0.87
9 (x=261)	0.10	0.87	0.89	0.10	0.88	0.90	0.10	0.91	0.89
5 (x=286)	0.10	0.81	0.90	0.10	0.83	0.91	0.11	0.86	0.91
6 (x=310)	0.09	0.72	0.85	0.08	0.76	0.86	0.09	0.81	0.85
10 (x=385)	0.13	0.62	0.84	0.12	0.67	0.89	0.13	0.70	0.87
11 (x=500)	0.16	0.32	0.62	0.16	0.36	0.70	0.17	0.38	0.70

D.5 Roller model vs. SWAN

D.5.1 Roller model

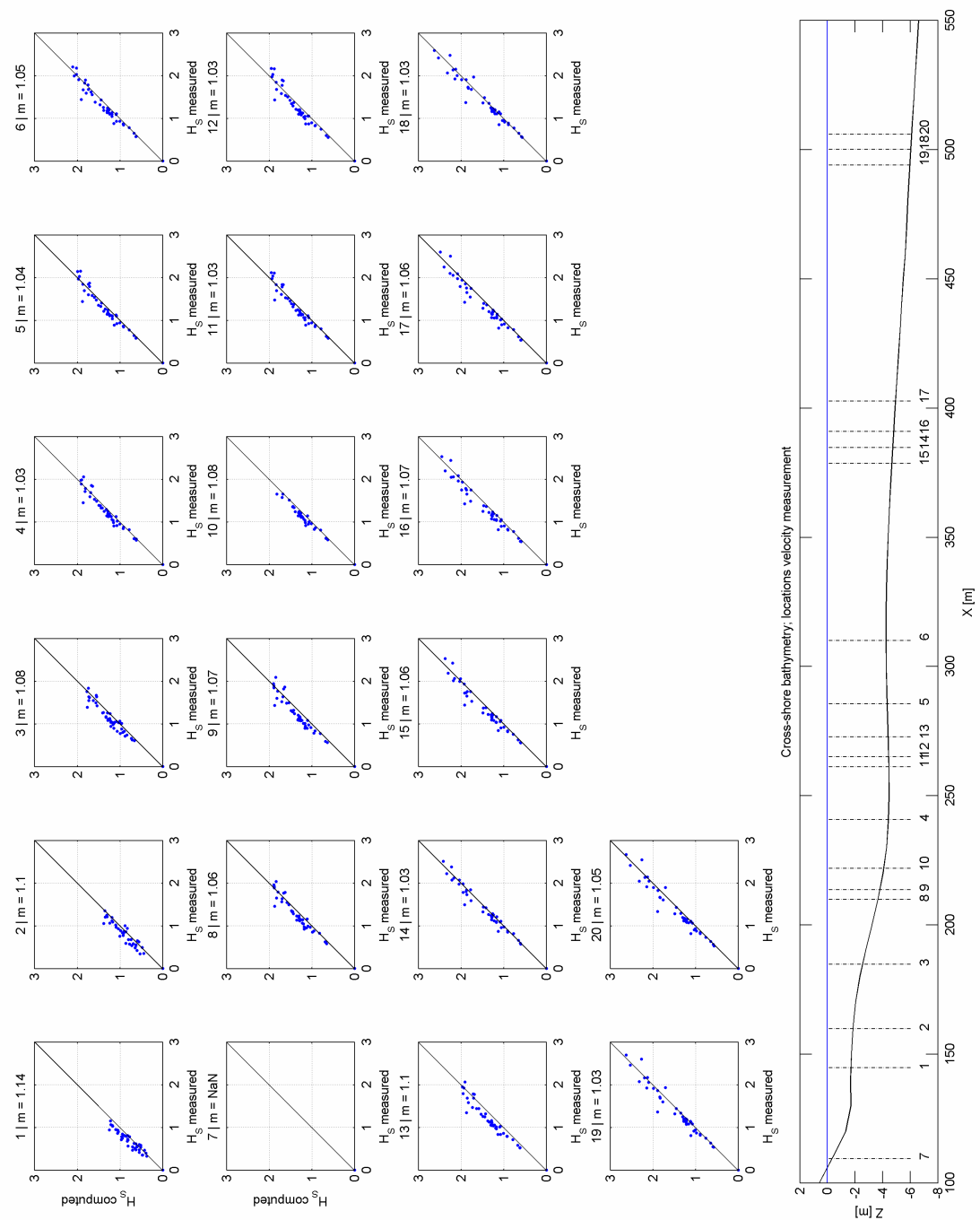


Figure D.5 Roller model computed wave height per cross-shore location of the measurements

D.5.2 SWAN

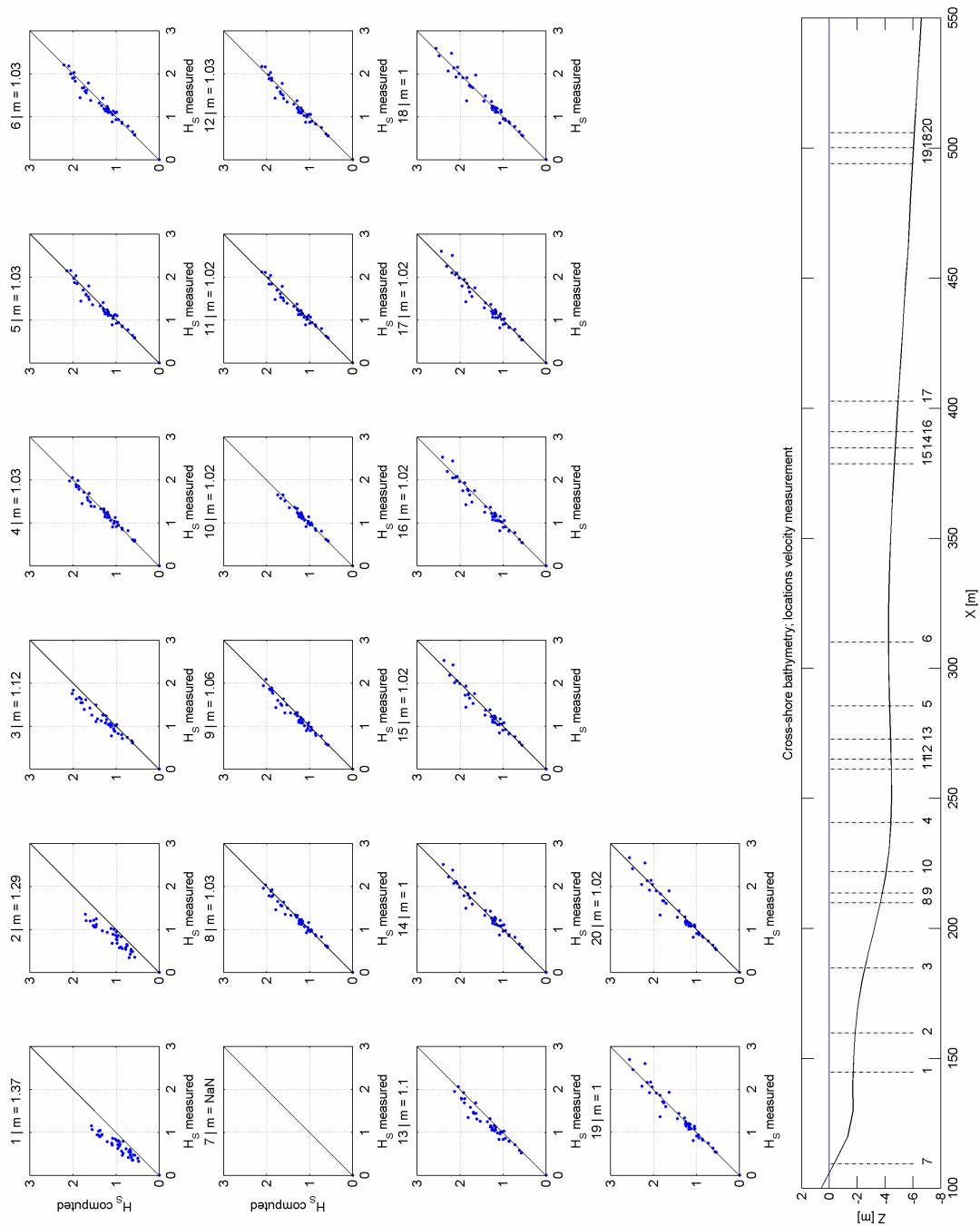


Figure D.6 SWAN computed wave heights per cross-shore location of the measurements