1DV modelling of wave-induced sand transport processes over rippled beds

M.Sc. Thesis

D.A. van der A

Enschede, June 2005

University of Twente
Faculty of Engineering Technology
Department for Water Engineering and Management
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Preface

This report forms the completion of my study Civil Engineering & Management at the Department for Water Engineering and Management, which is part of the Faculty of Engineering Technology at the University of Twente.

I would like to thank the members of the graduation committee dr.ir. Jan Ribberink and dr.ir. Marjolein Dohmen-Janssen for their support and supervision. Specifically, I would like to thank the third member of the committee, ir. Jebbe van der Werf, for the daily support and the detailed reviews of the numerous 'modelling reports' that ended up his desk.

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Abstract

Massive mining of sand from the middle and lower shoreface will be required in many European countries in the near future. For example, huge amounts of sand are necessary to nourish eroded beaches and for the construction of large-scale artificial islands. Technical knowledge of sand transport processes in these areas is essential for the determination of the sand budgets and to determine the morphological effects of sand mining on the shoreface and coast.

Except for storm conditions, the largest part of the shoreface bed is covered with wave-induced ripples. Fundamentally different physical processes determine wave-induced sand transport rates above plane and rippled beds. Above plane beds, most of the sand is transported onshore in a thin, near-bed layer. In contrast, above rippled beds, coherent vortex structures are generated periodically, which lead to the entrainment of sand into suspension to considerably greater heights. Beneath asymmetric waves this can lead to offshore directed net transport rates.

To determine the offshore and near-shore sand transport rates above rippled beds many types of models are developed. Most of these models are very complex and require long computational time and are therefore not normally implemented in coastal morphological models. From a practical point of view, relatively simple, one-dimensional model concepts are therefore preferred.

Recently, Davies and Thorne (2004) developed a one-dimensional vertical (1DV) model capable of describing the processes of vortex shedding and the associated entrainment of sediment at times of flow reversal. The key element is a sub-model in the lower layer equal to two ripple heights, in which the process of vortex shedding is represented by a time-varying eddy viscosity with peak values at flow reversal. In the upper layer, the model reverts to a standard turbulence-closure formulation. Suspended sediment is introduced at the ripple crest by a time-varying pick-up function. Although the model showed promising results for the Delta Flume data that is used in their research, further validation and improvement of the model is recommended.

A sensitivity analysis is carried out to investigate the influence of four important input parameters on the net transport rates: the median grain size, the wave asymmetry, the orbital velocity and the wave period. It is shown that the grain size and orbital velocity are of most influence on the predictions of the net transport rates. Variations of 10% in these parameters lead to variations in the predicted net transport rates ranging from 30-100%. Variations in wave asymmetry are only of influence for weak asymmetric waves and variations in the wave
period are only of minor influence on the net transport rates.

An assessment of the Davies and Thorne (2004) model is carried out with two new sets of full-scale flow tunnel measurements under several regular asymmetric wave conditions. The measurements are carried out in the Large Oscillating Water Tunnel (LOWT) at WL/Delft Hydraulics and the Aberdeen Oscillatory Flow Tunnel (AOFT) at Aberdeen University. Wave periods range from 5-10 s, orbital velocities range from 0.27-0.53 m/s and the median grain diameter of the sediment is 0.34 mm and 0.44 mm, respectively.

As part of the assessment, comparisons with the data are carried out. Predicted time-averaged and time-dependent concentration profiles, predicted ripple dimensions, as well as predicted net transport rates, are compared with the measurements. The time-averaged concentration profiles and net transport rates of the LOWT simulations show good agreement with the measurements. However, the time-averaged profiles and transport rates of the AOFT simulations are overestimated with approximately a factor 10, primarily caused by overestimations of the reference concentration with Nielsen’s (1986) prediction method in steep ripple regimes. Comparison with the measured time-dependent concentration profiles shows that the time-variation in the pick-up function is insufficient to reproduce the strong time-variation that follows from the measurements.

Following the results of the assessment, improvements are implemented in the original model. The improvements include a new formulation for the reference concentration by Van der Werf and Ribberink (2005). The key feature of this method is the dependency on the individual excursions of an asymmetric oscillation. The ripple predictor of Wiberg and Harris (1994) is replaced by the method of Mogridge et al. (1994). This method is also capable of predicting large ripple dimensions, in contrast to the original prediction method. The bedload formulation of Ribberink (1998) is included to represent the onshore transport component. Furthermore, an additional asymmetric term is included in the pick-up function to allow more time-variation and the phase moment of peak concentration is calibrated with the measured data.

The time-dependent concentration profiles of the improved model show better agreement with the measurements. However, still insufficient time variation can be produced. Validation of the improved model with an independent dataset based on net transport rates, shows that the predictions of the improved model are in better agreement with the measurements compared the predictions of the original model. However, uncertainty occurs in the choice of the bedload-related roughness height. Best overall results are generated with a bedload-related roughness height equal to 3D_90.

For further research it is recommended to validate the model with more laboratory data sets and with field data sets. Improvements of the model should be pointed at a more sophisticated description of the time-dependent processes, especially the phase difference between flow reversal and suspended cloud ejection.
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Chapter 1

Introduction

1.1 Project framework

Massive mining of sand from the middle and lower shoreface (depths of 10 to 30 m) in large-scale mining pits/areas will be required in many European countries to nourish beaches and coastal dunes in response to increased coastal erosion due to the expected sea level rise. Furthermore, large-scale reclamation of land and the construction of large-scale artificial islands (for industrial purpose: ports and airports) in coastal seas which are presently being considered, will also require huge amounts of sand as building material. Given the scale of these undertakings, the volume of sand required in the near future (10 to 20 years) will be of the order of 100 to 1000 m$^3$ per country surrounding the North Sea (Van Rijn and Walstra, 2002). To meet these demands, the existing sand mining areas need to be extended considerably and new potentially attractive areas should be explored and exploited.

Technical knowledge of sand transport processes in these areas is essential for the determination of the sand budgets and to determine the morphological effects of sand mining on the shoreface and coast. The accurate determination of offshore and near-shore sand budgets is a primary problem in coastal zone management for many of the European coasts. Existing sand transport models are still highly uncertain, due to uncertainty associated with the validity of these models in the shoreface environment. A specific class within the sand transport models are still highly uncertain, due to uncertainty associated with the validity of these models in the shoreface environment. A specific class within the sand transport models are still highly uncertain, due to uncertainty associated with the validity of these models in the shoreface environment. A specific class within the sand transport models are still highly uncertain, due to uncertainty associated with the validity of these models in the shoreface environment.

1.2 Sediment transport above rippled beds

In shallow water, waves produce an oscillatory horizontal flow at the edge of the boundary layer, usually close to the seabed. The period of this oscillatory flow is the same as the wave period, while the amplitude of the flow depends on the wave height, the wave period and the
flow depth. Various wave theories exist for the prediction of the kinematics under waves for given wave and depth conditions. The simplest theory is linear wave theory which applies to small amplitude waves in deep water. As waves propagate in water with decreasing depth the symmetric wave profile changes because the crest becomes sharper and the trough flatter. To predict waves of this shape, higher order theories have been developed, such as second and higher order Stokes theories and the cnoidal wave theory.

The wave-generated oscillatory flow at the sea bed produces lift and drag forces on individual sediment grains. When flow conditions exceed a certain threshold, the surface grains start to move to and fro. After a while the grains can collect together and form small triangular ridges, also known as rolling-grain ripples (Bagnold, 1946). According to Bagnold (1946), these ripples are stable for flow conditions less than two times the critical value. As flow conditions further increase a lee-side vortex develops, which becomes so strong that it is able to move the grains between two ripples, resulting in a growth of the ripple until the equilibrium geometry of these, so called, vortex ripples is reached. If the flow velocity is large enough the bed forms will be washed out and sheet flow will occur over a plane bed. Therefore, vortex ripples will occupy the regime bounded by threshold and sheet flow conditions. In terms of the grain roughness Shields parameter \( \theta_{2.5} \), the vortex ripple regime is approximately bounded by \( 0.05 \leq \theta_{2.5} \leq 1.0 \) or in terms of the mobility number \( \Psi \) the vortex regime is approximately bounded by \( 10 \leq \Psi \leq 156 \) (Clubb, 2001).

Sediment transport processes under asymmetric oscillatory flow over rippled beds are fundamentally different from those over plane beds. Above plane beds, momentum transfer occurs primarily by turbulent diffusion, while above rippled beds momentum transfer and the associated sediment dynamics in the near-bed layer are dominated by coherent motions, specifically the process of vortex formation above ripple lee slopes and the shedding of these vortices at times of flow reversal. In a near-bed layer of approximately 2 ripple heights the flow dynamics are dominated by the coherent periodic vortex structures, whereas above this layer the coherent motions break down and are replaced by random turbulence (Davies and Villaret, 1999). This leads to sediment in suspension to considerably greater heights compared to flat beds. The phase of sediment pick-up from the bottom is also significantly different above rippled beds. This has potentially important consequences for the net sediment transport rate under asymmetric waves. Despite the larger onshore (in the direction of wave propagation) orbital velocities the net transport can be directed offshore, which is illustrated in Figure 1.1.

In this figure, three ripples (B, C and D) are shown at various moments during the (asymmetric) flow cycle. In figure (a) the cloud C1 shed at the onshore flow reversal at ripple C, moves in the offshore direction towards ripple B. During the decreasing offshore flow velocity a new and much smaller vortex (C2) is formed at the stoss-side of the ripple (figure (b)). At times of offshore flow reversal, figure (c), this small vortex is shed and forms a small cloud which is moved in onshore direction (figure (d)). During the decreasing onshore flow, figure (e), a new larger vortex (C3) is formed at the ripple lee-side. At times of onshore flow reversal this large sediment cloud is thrown across the ripple crest level and is transported again in offshore direction (figure (f)). From this point on the process repeats itself, resulting in a net transport which is offshore directed. It has to be noticed here that presence of ripples not always leads to negative transport. Under some conditions, the onshore bedload component can predominate the suspended component, which results in onshore net transport.
1.3 1DV turbulence-closure approach

Numerous mathematical methods are available for predicting sediment transport processes in the rippled bed regime. In general, these methods can be divided in four types of models; time-averaged models, quasi-steady models, semi-unsteady models and unsteady models.

Time-averaged models were the first models that were developed to derive the sediment transport rate under waves and currents. The sediment transport rate is described at a time scale much longer than the wave period using the wave-averaged values of velocity and concentration. The disadvantage of this approach is that the wave-related transport component is not taken into account, which results in a total net transport that is always in the direction of the mean current. A widely-used time-averaged transport formula is developed by Buijker (1971).

Quasi-steady models are based on the assumption that the instantaneous transport rate is directly related to a certain power of the instantaneous near-bed flow velocity or bed shear...
stress. Due to this non-linear relation between the instantaneous transport rate and flow velocity, quasi-steady models will always predict a net transport rate in the direction of the largest velocity. The validity of quasi-steady models in the ripple regime is therefore questionable, because of the existence of significant phase differences between the instantaneous velocities and the concentrations due to the formation and ejection of vortices at the lee-side of the ripples. This latter phenomena is especially important in case of steep vortex ripples. One of the most widely-used quasi-steady models is the Bailard (1981) formula.

Semi-unsteady models take the effect of the observed time lag between the flow velocity and the sediment concentration under waves into account, without resolving the full time-dependent velocity and sand concentration field. Time lag effects become important and reduce the net transport rates when the response time of the sediment particles is not small compared to the oscillation period. Examples of semi-unsteady transport models which are validated with data in the ripple regime are the formulas of Nielsen (1988) and Dibajnia and Watanabe (1994, 1996).

Unsteady models compute the unsteady flow velocity and sand concentration profiles with the appropriate boundary conditions. The net sand transport rate is computed by vertical integration of the time- and bed-averaged sand fluxes. Unsteady models can be further divided into; turbulence-closure models, large eddy simulations (LES), direct numerical simulations (DNS), and discrete-vortex models.

LES, DNS, discrete-vortex models and 2DV turbulence-closure models are complex, require long computation time and are therefore not normally implemented in coastal morphologic models. The motivation for the present study has therefore been to continue with a relatively simple, 1DV modelling approach that includes an improved parametrisation of the near-bed vortex-layer above steep ripples, leading to improved practical predictions of local sand transport rates beneath waves.

1.4 Research objective

As mentioned before, there are still large uncertainties in the predictions of existing sand transport models. In relation with the current development of the 1DV model by Davies and Thorne (2004) the aim of the research is as follows:

To increase the knowledge of sediment transport under oscillatory flows in the rippled bed regime by validation and improvement of the 1DV sediment transport model by Davies and Thorne (2004), with new full-scale measurements from the Large Oscillating Water Tunnel and the Aberdeen Oscillatory Flow Tunnel.

1.5 Research questions

In order to reach the objective of this research it is necessary to define research questions, of which the answers will contribute to the fulfillment of this objective. The research questions are as follows:
1.6 Methodology

In the beginning of the project one of the key issues is to get familiar with the model itself. This is done by studying literature that is written about the model as well as working with the model itself. The aim of the literature study is to get a better understanding of the processes behind the model and to single out the elements of the model which can be subjected to improvement. Working with the model itself has the aim to get familiar with the program language it is written in and to understand what input is needed and what output can be generated. To understand the behaviour of the model it is essential to carry out a sensitivity analysis by varying several main input parameters.

After this first phase it necessary to run the original model with the experimental conditions to set benchmarks cases. These benchmarks should primarily be based on the time averaged net sediment transport rates, due to the overall importance of the transport rates. However, time-averaged and time-dependent concentration profiles are also of interest to investigate the individual transport processes. When the benchmark runs are completed a first assessment of the performance of the original model will be carried out.

The assessment of the original model will lead to insight in the processes of the model that are suitable for improvement. After it is clear which elements can be improved, and how they can be improved, they will be implemented in the model. With the new improved model, a second series of runs must be carried out with the experimental conditions. Comparison of these new outcomes with the outcomes of the original model, will give insight in the performance of the improved model. These new benchmark runs can consist again of the time-averaged and time-dependent concentration profiles as well as the net sediment transport rates.

The research can be finished by validation of the model with a different data set. After the validation process general conclusions can be drawn about the performance and application of the improved 1DV model.

1.7 Outline of the report

Chapter 2 describes the basic hydro- and sediment dynamics of the original 1DV model. The sensitivity of the net sediment transport as predicted by the model to several important parameters is studied in Chapter 3. Chapter 4 starts with a description of the new full-scale wave tunnel data. The assessment of the original model, based on several benchmark
runs, is described in the remaining part of this chapter. Based on the assessment and the benchmark runs, several improvements are proposed, which are described and implemented in the model in Chapter 5. The last two sections of this chapter are dedicated to the assessment of the improved model, based on comparison with the original dataset and a new independent dataset. Chapter 6 contains the discussion of the results of this research, and in Chapter 7 the main conclusions are given, together with recommendations for further research.
Chapter 2

1DV model

2.1 Introduction

Davies and Li (1997) developed the original 1DV turbulence-closure model capable of describing sediment transport for unsteady flow above a flat bed. This model was later extended by Davies and Thorne (2004) to cover the ripple regime as well. The key feature is an analytical, near-bed, sub-model to represent the processes of vortex shedding, and the associated sediment entrainment at times of flow reversal. In this lower layer, the model solves the time-dependent, phase-averaged momentum equation for the horizontally-averaged (over one ripple length) velocity and the continuity equation for the suspended sediment concentration. In the upper layer, above the vortex-dominated region, the model reverts to the standard turbulence-closure formulation, subject to matching conditions for velocity, turbulent energy, eddy viscosity and sediment concentration, at two ripple heights above the (undisturbed) mean bed level.

In Section 2.2 and 2.3 the governing hydro- and sediment dynamics and the basic assumptions of the 1DV model are outlined. The quantity of sediment in suspension strongly depends on the cycle-mean concentration at the ripple crest level, which is determined according to the formulation of Thorne et al (2002). This method is explained in Section 2.4. To reduce the input parameters for the model an adjusted version of the Wiberg and Harris (1994) ripple prediction method is used in the model to predict the ripple length and height based on flow characteristics, the grain-size and other parameters. A description of this method is given in Section 2.5. Finally, in Section 2.6 the main input parameters are given to run the model.

2.2 Hydrodynamics

The hydrodynamics in the model are described by the horizontally- and phase-averaged momentum equation (neglecting viscous stresses):

\[ \frac{\partial \langle u_p \rangle}{\partial t} = \frac{du_\infty}{dt} + \frac{\partial}{\partial z} \left( \frac{\tau_p}{\rho} \right) \]  \hspace{1cm} (2.1)

in which the subscript \( p \) denotes phase-averaging (averaging over a sufficiently large number of waves), making \( u_p \) the phase-averaged horizontal velocity. \( u_\infty \) is the free stream velocity and \( \tau_p \) the total shear stress. The brackets \( \langle \rangle \) denote horizontally-averaging over the ripple
wavelength ($\lambda$). For instance, regarding the horizontal velocity, this is done as follows:

$$\langle u_p \rangle = \frac{1}{\lambda} \int_0^{\lambda} u_p dx$$  \hspace{1cm} (2.2)$$

The free stream velocity is described by the second order Stokes theory as follows:

$$u_\infty = u_1 \cos(\omega t) + u_2 \cos(2\omega t)$$  \hspace{1cm} (2.3)$$

The total shear stress is made up of two components:

$$\frac{\tau_p}{\rho} = -\langle (u'w')_p \rangle - \langle u_p w_p \rangle$$  \hspace{1cm} (2.4)$$

with $u'$ and $w'$ the turbulent components of the horizontal and vertical velocity. The first component in Equation (2.4) is due to turbulent Reynolds stresses and the second component is associated with periodic velocity correlations (vortex formation). Sleath (1987), Ranasoma and Sleath (1992) and Perrier et al. (1995) showed in experimental and modelling studies that the latter component is much larger (in the near-bed layer over rippled and very rough beds) than the turbulent Reynolds stresses. By analogy with the gradient diffusion assumption and neglecting these Reynolds stresses, the total shear stress in the near-bed layer can be related to the mean flow velocity gradient as follows:

$$\tau_p = \rho K \frac{\partial \langle u_p \rangle}{\partial z}$$  \hspace{1cm} (2.5)$$

in which $K$ is the time- and height varying eddy viscosity.

Davies and Villaret (1999) found that the eddy viscosity was strongly time-varying with peaks near the instants of flow reversal in the free-stream. For the simulation of asymmetric waves, the eddy viscosity is given by the real part of the following expression:

$$K = K(1 + \varepsilon_0) + \varepsilon_1 e^{i\omega t} + \varepsilon_2 e^{2i\omega t}$$  \hspace{1cm} (2.6)$$

with $\varepsilon_0$ a small additive constant for weakly asymmetrical waves to constrain positiveness of $K$ throughout the wave cycle, defined by $\varepsilon_0 = |\varepsilon_1|^2/(8|\varepsilon_2|)$ The parameters $\varepsilon_1$ and $\varepsilon_2$ represent the asymmetric and symmetric components of $K$, with:

$$\varepsilon_1 = |\varepsilon_1| e^{i\varphi_1} \quad \text{and} \quad \varepsilon_2 = |\varepsilon_2| e^{2i\varphi_2}$$  \hspace{1cm} (2.7)$$

Here, the phase-angles $\varphi_1$ and $\varphi_2$ allow phase differences between the maximum free-stream velocity and the respective components of the eddy viscosity. Based on model comparison of drift profiles in the bottom boundary layer above rippled beds with five published laboratory data sets, Davies and Villaret (1999) suggested that the time-varying components of the eddy
viscosity should be varied in the following manner:

\[
|\varepsilon_1| = \begin{cases} 
10B & \text{for } B \leq 0.1 \\
1.0 & \text{for } B \geq 0.1
\end{cases}
\]  

(2.8)

\[
|\varepsilon_2| = \begin{cases} 
1 & \text{for } B \leq 0.1 \\
1 - \frac{40}{3}(B - 0.1) & \text{for } 0.1 \leq B \leq 0.15 \\
\frac{1}{3} & \text{for } B \geq 0.15
\end{cases}
\]  

(2.9)

with \( B \) the asymmetry parameter, defined by \( B = u_2/u_1 \). Davies and Villaret (1999) also found that the peak eddy viscosity occurred just ahead of flow reversal and suggested the following phase relationships for the components of the eddy viscosity:

\[
\varphi_1 = -\arccos(B) + \Delta \varphi \quad \text{and} \quad \varphi_2 = 2\varphi_1
\]  

(2.10)

with the phase lead of peak eddy viscosity ahead of flow reversal corresponding to \( \Delta \varphi = 4^\circ \).

The mean eddy viscosity (\( \bar{K} \)) is represented by Nielsen’s (1992) height-invariant time-averaged expression for very rough beds, given by:

\[
\bar{K} = c_k u_1 k_s \quad \text{for} \quad \frac{A_1}{k_s} < 5
\]  

(2.11)

with the empirical constant \( c_k = 0.005 \) and the near-bed excursion amplitude is given by \( A_1 = u_1/\omega \), with \( \omega \) the angular frequency. The bed roughness \( k_s \) depends on the ripple height (\( \eta \)) and ripple length (\( \lambda \)) as follows:

\[
k_s = 25\eta \frac{\eta}{\lambda}
\]  

(2.12)

In the upper layer the vortex structures are considered to have broken down in random turbulence (Ranasoma and Sleath, 1992). In this layer the flow is determined by the one-equation turbulence-closure formulation of Davies and Li (1997). In this formulation Equation 2.1 is solved, in which the eddy viscosity is related to the turbulence kinetic energy (\( k \)) and the vertical mixing length scale (\( l \)).

### 2.3 Sediment dynamics

The suspended sediment concentration in the model is solved, using the horizontally- and phase-averaged advection-diffusion equation:

\[
\frac{\partial \langle c \rangle}{\partial t} = \frac{\partial}{\partial z} \left( w_s \langle c \rangle + K_s \frac{\partial \langle c \rangle}{\partial z} \right)
\]  

(2.13)

where \( w_s \) is the settling velocity of the sediment, \( c \) the suspended sediment concentration and \( K_s \) the sediment diffusivity. Nielsen (1992) and later Thorne et al. (2002) found that the cycle-mean sediment diffusivity (\( \bar{K}_s \)) in the lower layer above rippled beds is significantly larger than the cycle-mean eddy viscosity, with \( \bar{K}_s = \beta \bar{K} \) and \( \beta = 4.0 \).
The bottom boundary condition for the sediment is expressed by the strongly time-varying sediment pick-up function, which associates the sediment entrainment with the vortex shedding process. The time-averaged condition at the ripple crest level for the pick-up function reads (Nielsen, 1992):

$$-K_s \frac{\partial \langle c \rangle}{\partial z} = w_s \langle c \rangle$$

(2.14)

In the time-varying version of the pick-up function both $K_s$ and $\partial \langle c \rangle/\partial z$ are time-varying functions, but asymmetry in sediment pick-up is only caused by the asymmetry in the eddy viscosity (Equation 2.6). The concentration gradient is expressed as symmetrical for simplicity, but with a period equal to half the wave period, to represent the increase in concentration at the two moments of flow reversal during each wave cycle. The sediment pick-up function can now be described by the real part of:

$$-K_s \frac{\partial \langle c \rangle}{\partial z} = w_s C_0 \frac{1}{2} \left( (1 + \varepsilon_0) + \varepsilon_1 e^{i \omega t} + \varepsilon_2 e^{2i \omega t} \right) \left( (1 + a_c e^{2i \omega t}) + c.c \right) \left( (1 + \varepsilon_0) + \frac{1}{4} A_c |\varepsilon_0| (e^{i(2\phi_c - 2 \phi_e)} + c.c) \right)$$

(2.15)

where $c.c$ denote the complex conjugate. The coefficient $a_c$ allows time-variation in the concentration gradient, because $a_c = A_c \exp(2i \phi_c)$ in which $A_c = 1$. The phase angle $\phi_c$, which is defined as $\phi_c = \phi_1 + 30(\pi/180)$, allows a phase difference between the concentration gradient and the velocity, and is set to 34° based on calibration of phase moment of the main concentration peak with the experimental data of Thorne et al. (2003). The parameter $C_0$ is the cycle mean reference concentration, which will be explained in the next section. Thus, in the quotient on the right hand side of Equation (2.15) the first term in the numerator arises from the time variation in the eddy viscosity and the second term expresses the (symmetric) time variation in the concentration gradient. The expression in the denominator makes sure that time-averaging fulfills Equation (2.14).

The value of the parameter $\beta$ has been assumed to revert smoothly from its value of 4.0 in the lower layer towards unity in the upper layer according to the power law rule:

$$\beta = 4.0 - 3.0 \left( \frac{z - 2\eta}{h - 2\eta} \right) $$

(2.16)

where the optimised value $\zeta = 0.4$ has been used here, and with $h$ the water depth. This procedure represents in some sense the gradual transition form 'convective' conditions in the lower layer to more 'diffusive' conditions in the upper layer (Davies and Thorne, 2004).

### 2.4 Reference concentration

The quantity of the reference concentration $C_0$ in Equation (2.15) is based on Nielsen’s (1986) empirical relationship:

$$C_0 = \gamma \theta_r^3$$

(2.17)

with $\gamma$ an empirical constant rescaled by Thorne et al. (2002) to 0.0022, based on large-scale wave-flume data. The ripple-related Shields parameter $\theta_r$, modifies the grain-related Shields parameter $\theta'$ for a plane bed in the following manner:
\[ \theta_I = \frac{\theta'}{(1 - \pi \eta A)^2} \]  
\[ (2.18) \]

in which the grain-related Shields parameter \( \theta' \) is based on Swart's (1974) friction factor \( f_w \) such that:
\[ \theta' = \frac{f_w U_I^2}{2(s - 1)gD_{50}} \]  
\[ \text{with} \quad f_w = \exp \left[ 5.213 \left( \frac{A_1}{2.5D_{50}} \right)^{-0.194} - 5.977 \right] \]  
\[ (2.19) \]

where \( s \) denotes the fraction of sediment density and fluid density, and \( g \) the gravity acceleration.

### 2.5 Sand ripple predictor

In this model the non-iterative procedure by Malarkey and Davies (2003) of the Wiberg and Harris (1994) oscillatory sand ripple predictor is used. Wiberg and Harris (1994) proposed a classification for both laboratory and field data. In this classification the ripples are subdivided into three groups: orbital, suborbital and anorbital. In the orbital regime the ripples depend on the near-bed wave orbital diameter \( d_0 (=2A_1) \), in the anorbital regime on \( D_{50} \), and in the suborbital regime on a combination of both parameters. Wiberg and Harris (1994) used the following parametrisation for the ripple steepness \( (\eta/\lambda) \) in terms of \( d_0/\eta \):
\[
\frac{\eta}{\lambda} = \begin{cases} 
0.17 & \frac{d_0}{\eta} \leq 10 \\
\exp \left[ -a_1 \ln \left( \frac{d_0}{\eta} \right) + a_2 \ln \left( \frac{d_0}{\eta} \right) - a_3 \right] & \frac{d_0}{\eta} > 10 
\end{cases}  
\]  
\[ (2.20) \]

with \( a_1=0.095, \ a_2=0.442 \) and \( a_3=2.28 \). For the ripple wavelength \( (\lambda) \) they proposed the following:
\[
\lambda = \begin{cases} 
\lambda_{\text{orb}} = 0.62d_0 & d_0/\eta_{\text{ano}} < 20 \\
\lambda_{\text{sub}} = \lambda_{\text{ano}} e^{f(d_0/\eta_{\text{ano}})} & 20 \leq d_0/\eta_{\text{ano}} \leq 100 \\
\lambda_{\text{ano}} = 535D_{50} & d_0/\eta_{\text{ano}} > 100 
\end{cases}  
\]  
\[ (2.21) \]

In this formulation, \( d_0/\eta_{\text{ano}} \) is given by the solution of Equation 2.20 with \( \lambda = \lambda_{\text{ano}} = 535D_{50} \), while, in equation 2.21 \( f(d_0/\eta_{\text{ano}}) = - \ln(\lambda_{\text{orb}}/\lambda_{\text{ano}}) \ln(0.01d_0/\eta_{\text{ano}})/\ln 5 \). With these two equations it is possible to determine the ripple dimensions iteratively.

Malarkey and Davies (2003) proposed the following relationship based on Equation 2.20 and the fact that \( \eta/\lambda = d_0/\lambda(d_0/\eta)^{-1} \):
\[
\frac{d_0}{\eta} = \exp \left[ B_2 - \sqrt{B_3 - B_1 \ln \left( \frac{d_0}{\lambda} \right)} \right]  
\]  
\[ (2.22) \]

where, \( B_1 = 1/a_1, \ B_2 = \frac{1}{2}(1 + a_2)B_1 \) and \( B_3 = B_2^2 - a_3B_1 \).
Equation 2.21 can be rewritten to the following equation:

\[
\frac{d_0}{\lambda} = \begin{cases} 
\frac{1}{0.62} & \frac{d_0}{\eta_{ano}} < 20 \\
\frac{d_0}{535D} e^{-\left(\frac{d_0}{\eta_{ano}}\right)} & 20 \leq \frac{d_0}{\eta_{ano}} \leq 100 \\
\frac{d_0}{535D} & \frac{d_0}{\eta_{ano}} > 100
\end{cases}
\] (2.23)

In this formula the limiting cases of \(d_0/\eta_{ano} = 20\) and 100 correspond to \(d_0/D = 1754\) and 5587, respectively. In a non-iterative way, with a given value of \(d_0/D\), the value of \(d_0/\lambda\) can be calculated from Equation 2.23 and with this value the ratio \(d_0/\eta\) can be calculated from Equation 2.22. Combinations of preceding ratios will ultimately lead to the ripple dimensions \(\eta\) and \(\lambda\).

The method used in the current 1DV model differs slightly from Malarkey and Davies (2003), because a maximum steepness of 0.14 is imposed based on the experimental data of Thorne et al. (2002), instead of the original maximum steepness of 0.17. The minimum steepness at which vortex formation and shedding occurs according Sleath (1984) is 0.105, which is used as minimum steepness in the current model. When one of these conditions is exceeded, the ripple height is adjusted such that the steepness fulfills this maximum or minimum.

### 2.6 Model parameters

The actual model is written in FORTRAN77 computer language, and makes use of a simple ASCII file in which the input parameters can be defined. An outline of these parameters is given in Appendix A. The temporal distribution of the model runs is 100 time steps per wave cycle, while the vertical distribution exists of 65 vertical intervals on a log-linear grid (grid distances become smaller with increasing water depth) between \(z = k_s/30\) and \(z = h\).

For each grid point the model calculates the (phase-averaged) horizontal velocity, suspended sediment concentration and sediment fluxes. Based on these parameters, the model also generates the cycle-averaged and depth-averaged horizontal velocities, concentrations and sediment fluxes.

Suspended and total sediment transport rates (per unit width) are calculated according to:

\[
q_s = \int_0^T \int_{\frac{h}{2}}^{\frac{h}{2}} \langle c_p \rangle \langle u_p \rangle dz dt 
\] (2.24)

\[
q_t = \int_0^T \int_0^h \langle c_p \rangle \langle u_p \rangle dz dt 
\] (2.25)
Chapter 3

Model sensitivity

3.1 Introduction

Before starting to further develop and improve an existing model it is necessary to investigate how the model performs. The performance of the current model is analysed on the basis of 1) a sensitivity analysis to several important input parameters, and 2) an assessment of the agreement between model predictions and experimental data (Chapter 4). Before any run is made with the current model a brief examination is carried out to determine the amount of wave cycles that gives a reliable representation of the phase-averaged transport rates and at the same keeps computational time within reasonable limits (Section 3.2). In Section 3.3 the influence of the grain size is examined. The grain size is for instance of influence on the prediction of the reference concentration ($C_0$). The influence of wave asymmetry is discussed in Section 3.4. The asymmetry influences the asymmetry in the eddy viscosity, which is directly related to the sediment pick-up. Another parameter of influence is the orbital velocity (Section 3.5) which influences a number of elements, for instance the eddy viscosity and the related pick-up function as well as the reference concentration and the prediction of the ripple dimensions. In Section 3.6 the influence of the wave period will be examined, which is of influence on the reference concentration as well as the eddy viscosity and ripple dimensions. To see the influence of the ripple predictor on the outcomes, all simulations will be compared with simulations, in which the measured ripple dimensions are imposed. Finally, in Section 3.7 presents a short summary and the main conclusions of this chapter. The ‘base case’ for this sensitivity analysis is condition T4-05 of Van der Werf (2004). The condition is obtained in the large oscillating water tunnel at WL|Delft Hydraulics. The median grain diameter ($D_{50}$) of this condition is 0.35 mm, with a wave period ($T$) of 5 s. The flow conditions are strong asymmetric ($B = 0.25$), with a near bed orbital velocity is 0.40 m/s. The measured ripple height for this conditions is 5.8 cm and the measured ripple length is 44 cm.

3.2 Wave cycles

In this section a short examination will be carried out to determine what number of wave cycles is needed to give a reliable representation of the phase-averaged sediment transport rates, while keeping the computational time limited. A number of runs is made with different amounts of wave cycles, namely 10, 100, 500, 1000, 5000 and 10,000 cycles. These runs are carried out for three different experimental series. These series all have different wave periods,
but corresponding values of the orbital velocities. The results are outlined in Table 3.1

<table>
<thead>
<tr>
<th>Test:</th>
<th>Wave cycles</th>
<th>T4-05</th>
<th>T4-07</th>
<th>T4-10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T4-05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-9.90·10⁻⁶</td>
<td>-39.98</td>
<td>-40.27</td>
<td>-29.48</td>
</tr>
<tr>
<td>100</td>
<td>-15.41·10⁻⁶</td>
<td>-4.99</td>
<td>0.12</td>
<td>0.00</td>
</tr>
<tr>
<td>500</td>
<td>-16.24·10⁻⁶</td>
<td>0.12</td>
<td>0.24</td>
<td>0.17</td>
</tr>
<tr>
<td>1000</td>
<td>-16.25·10⁻⁶</td>
<td>0.18</td>
<td>0.24</td>
<td>0.17</td>
</tr>
<tr>
<td>5000</td>
<td>-16.27·10⁻⁶</td>
<td>0.31</td>
<td>0.40</td>
<td>0.29</td>
</tr>
<tr>
<td>10000</td>
<td>-16.22·10⁻⁶</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Table 3.1:** Wave cycle influence on phase-averaged transport rates.

In this table it is assumed that the calculated transport rates for 10,000 wave cycles give the best representation of the phase-averaged transport rate. Therefore, $\Delta q_s$ gives the relative difference of the regarding transport rate, with the calculated amount at 10,000 wave cycles. It is clear from the table that from an amount of 500 wave cycles the difference becomes negligible. Because the total computing time is still relatively short (±90 s) a total number of 1000 wave cycles will be used from now on.

### 3.3 Median grain size

In this section the influence of the median grain diameter ($D_{50}$) on the net transport rate for series T4-05 is studied. Because the settling velocity depends on the grain diameter, and the settling velocity serves as an input parameter for the model, proportional variations in this parameter are imposed. First of all, the ratio between the measured and predicted settling velocity (according to Van Rijn (1993)) is calculated for the initial grain size ($D_0$=0.35 mm). This ratio (0.83 for these conditions) is multiplied with the calculated settling velocity for the various grain sizes in the applied range ($0 \leq D_{50}/D_0 \leq 2$), to convert the settling velocity of the bed material into the assumed settling velocity of the suspended material.

The results of the simulations are presented in Figure 3.1. In Figure 3.1(a) the influence on the net sediment transport for both imposed and predicted ripple dimensions are presented, while in Figure 3.1(b) the predicted ripple dimensions are outlined. Note that the negative transport rates are plotted on the (positive) y-axis in Figure 3.1. In Figure 3.1(a) can be seen that for large grain sizes the net transport is minimal. When the grain size decreases the net transport increases, following a somewhat exponential curve. This increase in transport for smaller grain sizes is as expected, as small grains are simply easier to lift and move under the same flow conditions because of their smaller weight. For grain sizes larger than approximately 0.025 cm ($D_{50}/D_0=0.7$), the net transport is larger in the case of predicted ripple dimensions. For $D_{50}$=0.025 cm both rates are equal and for smaller grain sizes the transport rates in the case of imposed ripples become larger.

The effect of the grain size on the net transport rate can be explained by means of the formulation for the reference concentration, Equation 2.17 and the related formulations for the ripple- and grain-related Shields parameters. An increase in the grain diameter leads to
3.3 Median grain size

Figure 3.1: Influence of median grain diameter on the net sediment transport rates [a] where $D_0$ equals the initial median grain diameter of 0.035 cm, and on the predicted ripple dimensions [b] for series T4-05. In figure (b) the solid lines denotes the predicted ripple steepness, the dashed line the ripple length and the dash-dotted line the ripple height. The imposed dimensions are represented by the symbols, with □ ripple height, ○ ripple length and x ripple steepness.

an increase in the friction factor. In the formulation of the grain-related Shields parameter the median grain diameter is present in the numerator as well as the denominator, but due to the weak increase of the friction factor ($f_w \sim e^{D_{50}^{0.194}}$) the $D_{50}$ in the denominator dominates, leading to a decrease in the Shields parameter when $D_{50}$ increases. Thus, a decrease in the grain diameter will lead to an increase in the grain-related Shields parameter, which by means of Equation 2.18 leads to an increase in the reference concentration of Equation 2.17. The reference concentration is directly of influence on the prediction of the concentration profiles. Thus, by means of Equation 2.24 and the formulation for $C_0$, the grain diameter influences the net transport. The dependency of $C_0$ on $\theta^3$ explains the exponential shape of the curves in Figure 3.1(a). The variations in $C_0$ are not solely responsible for the changes in the net transport, because the changes in settling velocity contribute to the sediment pick-up: lower settling velocities facilitate the pick-up, while higher settling velocities reduce the pick-up. More pick-up leads to more sediment in suspension and thus to stronger filled concentration profiles, which lead to more transport. A reduction in the settling velocity for smaller grain sizes also means that the settling of the particles takes more time. This results in more sediment in suspension and thus to an increase in the net transport.

In Figure 3.1(b) the measured and predicted ripple dimensions are outlined. The same measured dimensions, represented by the symbols, were imposed during the entire grain diameter range. The predicted ripple height is lower than the imposed ripple height, up to a median grain diameter of 0.035 cm ($D_{50}/D_0=1.0$). After this value the ripple height increases further until $D_{50}=0.05$ cm ($D_{50}/D_0=1.4$). For even larger grain sizes the predicted ripple dimensions remain constant, with a predicted height of approximately 7.5 cm. The ripple length shows almost the same behaviour; for increasing grain size the ripple length continuously increases. At a $D_{50}$ of 0.04 cm ($D_{50}/D_0=1.1$) both measured and predicted ripple length are equal and from approximately 0.05 cm the ripple length becomes constant with a predicted length of almost 55 cm. The result of the simultaneous course of both graphs is that the ripple steepness...
stays constant during the entire range, as it is the ratio of the ripple height and the ripple length. The difference with the measured steepness is that the predicted steepness is higher (0.14) than the measured steepness (0.13).

The transition from increasing ripple dimensions to constant dimensions at $D_{50}/D_0=1.4$ is caused by the shift of the ripple dimensions from the 'sub-orbital' to the 'orbital' regime. In the 'sub-orbital' regime the ripple length is dependent on the grain diameter and in the 'orbital' regime the ripple length becomes independent of the grain diameter (see Equation 2.23). The simultaneous course of the ripple height is the result of the imposed maximum ripple steepness of 0.14. When the actual predicted ripple height exceeds this maximum the ripple height is calculated by multiplying the maximum steepness of 0.14 with the predicted ripple length, thus leading to a linear relationship between both dimensions. Because the maximum ripple steepness is already exceeded for the lowest grain size ($D_{50}/D_0=0.6$), and the steepness tends to increase for increasing grain sizes, this linear relationship is visible throughout the entire $D_{50}$ range.

Now that the behaviour of the ripple dimensions is known, the differences between the 'imposed' and 'predicted' curves in Figure 3.1(a) can be explained. It is already explained that a higher ripple steepness leads to a larger reference concentration. The other parameter that is influenced by the ripple dimensions is the mean eddy viscosity, Equation 2.11, with the roughness height related to the ripple height and steepness ($k_s = 25\eta^2/\lambda$). Thus an increase in the ripple steepness or ripple height leads to an increase in the roughness parameter, which directly leads to a higher mean eddy viscosity. An increase in the eddy viscosity leads to stronger vortex formation and also increases the amount of sediment pick-up, thus resulting in more sediment in suspension and higher transport rates. If the condition in Equation 2.11 is exceeded, the bed is not categorised as fairly rough (Nielsen (1992), Davies and Villaret (1999)) which makes the model not applicable in these situations. This condition is also the reason for the abrupt ending of the 'predicted' graphs in Figure 3.1 at $D_{50}/D_0 = 0.6$. In Figure 3.1(a) the higher 'imposed' transport rates for $D_{50}/D_0 \geq 0.7$ can be ascribed to the reference concentration as well as the mean eddy viscosity. Due to the higher predicted steepness compared to the measured steepness throughout the whole $D_{50}$ range, the reference concentration ($C_0$) is predicted higher. A higher reference concentration leads to more pick-up and more sediment in suspension, which leads to more transport. The difference between the measured and predicted $C_0$ stays constant throughout the whole grain size range because $\lambda/\eta$ stays constant. The lower steepness of the 'imposed' graph in Figure 3.1(a) can thus be ascribed to the mean eddy viscosity. For $D_{50}/D_0 \leq 1.6$ the ripple height is decreasing, which results in lower roughness heights and a lower mean eddy viscosity. As mentioned before the decrease in eddy viscosity leads to less sediment in suspensions and thus to less transport. For $D_{50}/D_0 \leq 0.7$ the mean eddy viscosity decreased that much that the net transport even becomes less than the net transport in case of imposed ripple dimensions, despite the still larger $C_0$ values.

Summarising it can be said that the overall sensitivity for changes in the median grain diameter is relatively large. An increase in $D_{50}$ of 10% leads to a decrease in the net transport rate of 20%, while a decrease of 10% in $D_{50}$ leads to an even larger change in the net transport of approximately 30%. For small grain diameters the model with use of the ripple predictor becomes inapplicable, since the predicted ripple dimensions become very small and fall outside
the vortex ripple regime.

3.4 Wave asymmetry

The asymmetric wave motion in the tunnel is described by the second-order Stokes theory in which \( u_1 \) is referred to as the first harmonic and \( u_2 \) the second harmonic component of the horizontal velocity. As mentioned before, the asymmetry of a wave is expressed through parameter \( B \), which is defined by \( B = u_2/u_1 \). To preserve a regular asymmetric profile with one peak in positive and one peak in negative direction, the asymmetry is bounded to a maximum value of 0.25 (see Figure 3.2).

![Figure 3.2: Second-order Stokes velocity profiles for high and low asymmetry parameters.](image)

As mentioned in Section 2.6 both harmonic components are needed as input for the model. To determine these components, the following relationships are used:

\[
\begin{align*}
    u_1 &= \sqrt{\frac{2u_{\text{rms}}^2}{1 + B^2}} \\
    u_2 &= \sqrt{2u_{\text{rms}}^2 - u_1^2}
\end{align*}
\]

which are derived by merging the formulation for \( B \) and the root mean square of the orbital velocity, given by:

\[
u_{\text{rms}} = \sqrt{\frac{1}{2}(u_1^2 + u_2^2)}
\]

To simulate the variations in asymmetry, adjustments in the harmonic components are applied. First of all \( u_1 \) is determined for various values of \( B \) according to Equation 3.1. With use of Equation 3.2 and the calculated values of \( u_1 \) the value of the second harmonic component is determined. In both calculations the root mean square of the near-bed orbital velocity is kept constant to reduce the influence of changes in this parameter on the net transport. In Section 3.5 the influence of this parameter will be discussed separately. The consequence of the fixed \( u_{\text{rms}} \) is that variations in \( u_1 \) must be imposed, which influences the prediction
of the ripple dimensions and the reference concentration as discussed before, but also the mean eddy viscosity from Equation 2.11. However, because the reduction in \( u_2 \) delivers the main contribution to the changes in asymmetry, there are only minimal changes in \( u_1 \) with a maximum variation of only 3%, so the influence of this parameter is negligible. The results of the simulations are outlined in Figure 3.3.

![Figure 3.3](image)

**Figure 3.3:** Influence of wave asymmetry on net sediment transport rates for the imposed ripple conditions and the predicted ripple dimensions (a) and the influence of the wave asymmetry on the prediction of the ripple dimensions (b). In figure (b) the solid line denotes the predicted ripple steepness, the dashed line the ripple length and the dash-dotted line the ripple height. The imposed dimensions are represented by the symbols, with □ ripple height, ○ ripple length and x ripple steepness.

In Figure 3.3(a) the influence on the net sediment transport rate is outlined for the imposed and predicted ripple dimensions. When the asymmetry is equal to 0, meaning symmetrical wave conditions, there is no net sediment transport. This was also expected, because equal amounts of sediment are transported in on- and offshore direction during each wave cycle. When asymmetry increases the net transport increases as well. For both cases this increase is almost linear for \( B \leq 0.1 \). For the 'predicted' case this increase is slightly stronger than for the 'imposed' case, resulting in higher net transport rates compared to the 'imposed' case in this region. For \( 0.1 \leq B \leq 0.15 \) both transport rates still increase very slightly but in this region not linearly with \( B \) anymore and for \( B \geq 0.15 \) the net transport rates do not vary at all for increasing asymmetry.

To give an explanation for the course of these graphs it is necessary to take a closer look at the formulation of the time-dependent eddy viscosity \( K \). From Equation 2.8 it can be seen that the asymmetric component gradually achieves greater importance when \( B \) increases, which can also be seen in Figure 3.4(a) where the time-dependent eddy viscosity from Equation 2.6 is plotted for different values of \( B \). In this figure it can be seen that for \( B=0 \) up to \( B=0.1 \) the first peak strongly increases and the second peak strongly decreases. This first peak represents the vortex formation at the first flow reversal (from positive to negative) and the second peak the vortex formation at the opposite flow reversal. The increase in sediment pick-up that is accompanied by these peaks results in a larger amount of sediment that is transported after the first flow reversal in negative direction than after the second flow.
reversal in positive direction. A possible explanation for the linear increase of the net offshore transport for $B \leq 0.1$, is that the difference between both peaks also increases linearly with increasing asymmetry in this region, see Equation 2.8 and Equation 2.9.

In the next region in Figure 3.3(a), between $B = 0.1$ and 0.15, the importance of the asymmetry increases further (see Equation 2.9 and Figure 3.4(b)), while the total transport only increases slightly. Figure 3.5(a), where the total transport is divided in a wave- and current-related component, shows that the wave-related transport even decreases. The reason why the total transport rate still increases is the stronger increase of the current-related transport compared to the decrease in wave-related transport.

![Figure 3.4: Time-dependant (a) and time-averaged (b) profiles of $K$ for various asymmetry parameters.](image)

The change in direction of the current-related transport (at $B=0.12-0.13$) can be explained on the basis of Figure 3.5(b). Here it can be seen that the contribution of the offshore part of the net current in the lower layer ($z \leq 2\eta$) increases for increasing values of the asymmetry parameter. For values of $B$ larger than approximately 0.12 the negative contribution even becomes larger than the positive contribution, resulting in negative current-related transports rates. However, this behaviour still does not explain the decrease in the wave-related transport. A probable reason could be the moment of the concentration peak at times of flow reversal. When asymmetry increases and the viscosity and concentration peaks hardly shift with the moment of flow reversal, a substantial part of the concentration peak would be moved in onshore direction, which could cause the reduction in the negative transport. More of this time-dependent behaviour will be discussed later in Chapter 4. For $B \geq 0.15$ the total net transport remains constant which is the result of the constant eddy viscosity, as can be seen in Figure 3.4(b) were the eddy viscosity is (almost) equal for $B=0.15$ and $B=0.25$.

In Figure 3.3(b) the ripple dimensions are outlined. As can be seen, the ripple dimensions stay constant when asymmetry is increased, which also results in a constant ripple steepness. The ripple length is underestimated with approximately 3 cm, but the measured and predicted ripple height almost match perfectly. The result of this underestimated ripple length is that the predicted ripple steepness is somewhat higher compared to the imposed case.
Figure 3.5: Influence of wave asymmetry on the current- and wave-related sediment transport components for the imposed and predicted ripple conditions (a) and vertical net profiles for different asymmetry parameters (b).

The ripple dimensions do not change with asymmetry because no changes were made in parameters that influence the ripple dimensions. As mentioned before the asymmetry increased by decreasing $u_2$, which is not of influence on the prediction of the ripple dimensions. However, very minor adjustments in $u_1$ were necessary to keep $u_{rms}$ constant. These adjustments lead to negligible variations in the ripple dimensions.

The difference between the ‘predicted’ and ‘imposed’ transport rates in Figure 3.3(a) are caused by the difference in predicted and measured ripple steepness. The slight increase in measured and predicted ripple steepness from 0.13 to 0.14, leads to a strong increase in $C_0$ of approximately 30%. This increase in $C_0$ leads to an increase in the whole concentration profile with the same amount and apparently to an increase in the net transport of approximately 30%. The influence of the mean eddy viscosity is much less because $k_s$ only increases with 7% due to the increase in ripple steepness.

It can be concluded that variations in the asymmetry are only of influence on the net transport rates for low asymmetry parameters ($B \leq 0.1$). For higher asymmetry parameters the net transport is hardly influenced by changes in asymmetry, which is mostly caused by the relation between the (a)symmetric components of $K$ and the asymmetry parameter $B$ (Equation 2.8). Since the experimental conditions in this research all consist of strongly asymmetric waves ($B = 0.25$), no uncertainty should be expected regarding the asymmetry of the flow. The relative differences between the net transport rates with imposed and the net transport rates with predicted ripple dimensions are constant, since variations in asymmetry do not influence the predicted ripple dimensions.
3.5 Orbital velocity

The variations in orbital velocity ($u_{\text{rms}}$) are imposed by changing the harmonic velocity components, while keeping the wave asymmetry parameter constant. Figure 3.6(a) shows the impact of varying $u_{\text{rms}}$ on the net sediment rate transport for both imposed and predicted ripple dimensions. Both graphs show an exponential rise in the net transport for increasing $u_{\text{rms}}$ and the net transport for the predicted ripple dimensions is larger during the entire $u_{\text{rms}}$ range.

The strong increase in the net sediment transport can be related to the strong increase in the reference concentration, because $C_0 \sim u_1^6$. As mentioned before, the sediment transport is directly influenced by the increase in $C_0$. Another contribution is delivered by the increasing eddy viscosity. The increase in the harmonic component $u_1$ leads, by means of $A_1$, to an increase in the mean eddy viscosity (Equation 2.11). Due to the linear relationship between both these parameters the contribution is much less compared to the contribution of the reference concentration.

In Figure 3.6(b) the ripple dimensions are outlined. Both ripple dimensions increase for $u_{\text{rms}} \leq 0.36 \text{ m/s}$ (corresponding to $u_{\text{rms}}/u_0 \leq 0.9$), after which they start to decrease. Thus first the ripples grow with increasing wave motion and for larger $u_{\text{rms}}$ they tend to get washed out. The prediction of the ripple height is good as it closely approaches the measured height at $u_{\text{rms}}/u_0 = 1$. The ripple length is underestimated with a few centimetres, which also explains the higher estimations of the ripple steepness. The constant ripple steepness throughout almost the whole $u_{\text{rms}}$ range is again caused by the maximum imposed ripple steepness of 0.14. Because the steepness in reality exceeded this maximum, the ripple height is directly coupled to the length which explains the simultaneous course of both graphs.

Figure 3.6: Influence of orbital velocity on net sediment transport [a] and on the prediction of ripple dimensions [b]. Here, $u_0$ corresponds to $u_{\text{rms}} = 0.4 \text{ m/s}$. In figure (b) the solid lines denotes the predicted ripple steepness, the dashed line the ripple length and the dash-dotted line the ripple height. The imposed dimensions are represented by the symbols, with □ ripple height, ○ ripple length and x ripple steepness.
The increase in ripple dimensions for low values of $u_{\text{rms}}$ can be explained on the basis of Equation 2.23. In the orbital regime, the ripple length is only dependent on $u_1$, by means of orbital diameter ($d_0$). Thus as $u_{\text{rms}}$ increases, the ripple dimensions increase at the same rate. At $u_{\text{rms}}/u_0 = 0.75$ the velocity increased that much that a shift to the sub-orbital regime takes place. After $u_{\text{rms}}/u_0 = 0.75$ the ripple dimensions still slightly increase after which they start to decrease, which is due to the exponential relationship between $d_0$ and the ripple dimensions in this regime. Despite the variations in both the ripple length and height, the steepness stays constant during the largest part of the velocity range. Only for the highest $u_{\text{rms}}$ values the steepness decreases a bit, caused by a stronger decrease in the ripple height compared to the length.

Now that the behaviour of the ripple dimensions is clear, an explanation can be given for the difference between the 'imposed' and 'predicted' graphs of Figure 3.6(b). This difference can again be related to the difference in measured and predicted ripple steepness. The difference in steepness of 0.01 leads to a large difference between the measured and predicted values of $C_0$, which is directly of influence on the net transport rates. The contribution of the differences in $\eta$ to the mean eddy viscosity and transport predictions are minimal because the differences are minimal in the most important regime for $0.6 \leq u_{\text{rms}}/u_0 \leq 1.4$.

Summarising it can be said that the calculations with use of the ripple predictor do not lead to differences in the behaviour of the model, but the use of the ripple predictor does lead to higher transport rates. The overall sensitivity for changes in the near-bed orbital velocity is relatively large, as an increase of 10% in $u_{\text{rms}}$ leads to an increase in the net transport of more than 100%. Due to the exponential relationship this difference even becomes larger for larger values of $u_{\text{rms}}$.

### 3.6 Wave period

In Figure 3.7(a) it can be seen that for the 'imposed' case the net transport rate gets infinitely large for very small wave periods and ultimately will be zero for very large wave periods. This behaviour can be expected as for very large wave periods the velocity and concentration gradients become very weak, resulting in negligible small sediment fluxes. However, for very short periods, these gradients become very strong, intensifying the turbulent effects. For wave periods smaller than 2.5 s ($T/T_0 \leq 0.5$) the 'predicted' transport rates are significantly smaller than for the 'imposed' case. For periods larger than 2.5 s the 'predicted' transport rates are larger than the 'imposed' rates, but the differences become smaller as $T$ increases.

In an analytical manner, the exponential course of the net transport can be subscribed to the prediction of the reference concentration. Because the friction factor $f_w$ decreases exponentially with increasing $T$ (by means of $A_1$), the same behaviour occurs for $C_0$, due to the dependency of $C_0$ on the friction factor ($C_0 \sim f_w^3$). Another point is that for short periods the sediment has not enough time to settle, resulting in these very high transport rates. The mean eddy viscosity and thus the sediment diffusivity are not influenced by $T$, which means they do not influence the variations in transport rate.

Due to the dependency of the ripple dimensions on the orbital diameter, which equals $Tu_1/\pi$,
3.6 Wave period

Figure 3.7: Influence of period on net transport rates (a) with $T_0 = 5$ s and the predicted ripple dimensions (b). In figure (b) the solid lines denotes the predicted ripple steepness, the dashed line the ripple length and the dash-dotted line the ripple height. The imposed dimensions are represented by the symbols, with □ ripple height, ○ ripple length and x ripple steepness.

no differences exist between the prediction of the ripple dimensions in Figure 3.7(b) and Figure 3.6(b). In the previous section $u_{rms}$ is increased by increasing $u_1$, thus an increase of 10% in $u_{rms}$ also means an increase in $u_1$ of 10% (see Equation 2.3) and has the same impact on the ripple dimensions as an increase of 10% in the wave period. Thus Figure 3.7(b) needs no further explanation as the behaviour as identical to the behaviour of Figure 3.6(b).

Now that the course of the predicted ripple dimensions are clear an explanation can be given for the behaviour of the ‘predicted’ graph in Figure 3.6(a). First of all the ‘predicted’ graph does not cover the full wave period range as for $T \geq 8$ s ($T/T_0 \geq 1.6$) the conditions do not meet the $A_1/k_s \leq 5$ criterion of Equation 2.11 making the model inapplicable for these conditions. For $2.5 \leq T \leq 8$ s the ‘predicted’ transport rates are larger than the ‘imposed’ transport rates, because the reference concentration is overestimated due to the high ripple steepness. The differences between the measured and predicted rates in this region are not constant, as the differences are minimal at the boundaries and maximal for $0.8 \leq T/T_0 \leq 1.0$. This behaviour is related to the prediction of the ripple height in the same region. For $0.8 \leq T/T_0 \leq 1.0$ the predicted ripple height is approximately the same as the measured ripple height, thus the overestimated reference concentration dominates. Closer to the boundaries the ripple height is underestimated, which leads to a lower mean eddy viscosity and consequently, to lower concentrations.

It can be concluded that variations in the wave period are of minor influence on the net transport. Especially in the most important regime for this research ($T \geq 4$ s), variations in $T$ of 10% only lead to variations in the net transport of approximately 5%. Due to the exponential relationship between $C_0$ and $T$ this influence becomes even less for periods larger than 5 s. Variations in transport between imposed and predicted ripple dimensions are only of influence for very short periods ($T \leq 4$ s), due to the small predicted ripple dimensions. However, such periods are not very common in field conditions.
3.7 Conclusions

In this chapter the sensitivity of the net transport is investigated for four different parameters; the median grain diameter, the wave asymmetry, the near-bed orbital velocity and the wave period. For each parameter two different runs are carried out, one with imposed ripple conditions and another with predicted ripple conditions by means of the non-iterative procedure by Malarkey and Davies (2003) for the Wiberg and Harris (1994) oscillatory sand ripple predictor.

It seems that the net transport is most sensitive for variations in the grain diameter and orbital velocity. Both these parameters have strong influences on the prediction of the reference concentration, which determines the amount of sediment pick-up during each wave cycle, and on the pick-up formulation itself. Variations in the grain diameter of 10% lead to variations in the predicted transport rates of 30-40%, while variations in the orbital velocity of 10% lead to very large variations in the net transport rates of approximately 100%.

Variations in asymmetry only influence the net transport rates for small asymmetry parameters ($B \leq 0.1$). When asymmetry further increases to its maximum value ($0.1 < B \leq 0.25$), the transport rates remain constant, because the decrease in wave-related transport is equal to the increase in current-related transport. The predicted ripple dimensions are not influenced by changes in asymmetry. Therefore, relative differences between the transport rates with predicted and imposed ripple dimensions remain constant in the entire asymmetry range. Variations in the wave period are also of minor influence on the net transport rates. Especially in the most important regime for this research ($T \geq 4$ s), variations in $T$ of 10% only lead to variations in the net transport of approximately 5%.

The predicted ripple dimensions are in general smaller than the measured ripple dimensions. These smaller ripple dimensions lead to higher estimations of the reference concentration and in general to higher net transport rates compared to the transport rates where the measured ripple dimensions are imposed.
Chapter 4

Model assessment

4.1 Introduction

This chapter contains the results of the so called 'benchmark' simulations, which are a series of runs with the original model of Davies and Thorne (2004) bases on several experimental conditions. The outcomes will be analysed to give a first impression of the original model and will be used later for comparison with the results of the improved model. The data used in this research is obtained in the large oscillating water tunnels at WL|Delft Hydraulics and at the University of Aberdeen Fluids Laboratory. A description of these facilities, the experimental conditions and the type of measurements that were carried out are described in Section 4.2. From the previous chapter followed that the use of the ripple predictor can lead to difference in the predicted transport rates. Therefore, the predicted ripple dimensions are compared with the measured ripple dimensions in Section 4.3. Section 4.4 contains a comparison of the measured and predicted time-averaged concentration profiles. The bottom boundary condition and vertical mixing scale are indicators how well the concentration profiles are predicted. These elements are described separately in Section 4.5 and Section 4.6 respectively. For some experiments, time-dependent concentration profiles were also measured. A comparison of these measurements with the model predictions is outlined in Section 4.7. In Section 4.8 the most general and important output, the net sediment transport rates, are compared with the measured transport rates. Finally, in Section 4.9 the results are discussed and the conclusions of this assessment of the original 1DV model are outlined.

4.2 Experimental data

Two series of experiments were carried out in large laboratory water tunnels. The advantage of these large water tunnels is that they can reproduce the near-bed wave motion with periods and amplitudes equivalent to those occurring at sea. In contrast with real propagating waves, the same phase occurs at every location along the tunnel, and vertical motions are absent. Therefore, streaming of the type of Longuet-Higgins is not present in wave tunnels.

The first series of experiments was carried out in the Large Oscillating Water Tunnel (LOWT) at WL|Delft Hydraulics and the second series at the Aberdeen Oscillatory Flow Tunnel (AOFT) at the University of Aberdeen Fluids Laboratory. Although both series have been carried out in more or less identical facilities and both series consist of regular asymmetric
waves, there are still fundamental differences between the experimental conditions and the data that is obtained. Therefore, a short outline of both experiments is given in the next sections.

4.2.1 LOWT experiments

The system basically consists of a vertical U-tube with an open leg and the other leg provided with a piston which generates the oscillating water motion in the tunnel. The water tunnel is 14 m long with a 0.3 m wide and 1.1 m high glass-sided rectangular test section. The tunnel is designed to place a sediment bed of 0.3 m, leaving the upper 0.8 m for the oscillating flow. In Appendix B a more specific description of the tunnel is given. An outline of the measured conditions are given in Table 4.1.

<table>
<thead>
<tr>
<th>Test</th>
<th>$T$ (s)</th>
<th>$u_{rms}$ (ms$^{-1}$)</th>
<th>$D_{50}$ (mm)</th>
<th>$\eta$ (m)</th>
<th>$\lambda$ (m)</th>
<th>$\Psi$ (-)</th>
<th>$c_r$ (mms$^{-1}$)</th>
<th>$B$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4-05</td>
<td>5.0</td>
<td>0.40</td>
<td>0.35</td>
<td>0.058</td>
<td>0.44</td>
<td>56</td>
<td>-0.08</td>
<td>0.25</td>
</tr>
<tr>
<td>T5-05</td>
<td>5.0</td>
<td>0.50</td>
<td>0.35</td>
<td>0.051</td>
<td>0.46</td>
<td>88</td>
<td>-0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>T4-07</td>
<td>7.5</td>
<td>0.40</td>
<td>0.35</td>
<td>0.086</td>
<td>0.62</td>
<td>56</td>
<td>0.14</td>
<td>0.25</td>
</tr>
<tr>
<td>T5-07</td>
<td>7.5</td>
<td>0.50</td>
<td>0.35</td>
<td>0.101</td>
<td>0.75</td>
<td>88</td>
<td>0.03</td>
<td>0.25</td>
</tr>
<tr>
<td>T4-10</td>
<td>10.0</td>
<td>0.40</td>
<td>0.35</td>
<td>0.102</td>
<td>0.76</td>
<td>56</td>
<td>0.24</td>
<td>0.25</td>
</tr>
<tr>
<td>T5-10</td>
<td>10.0</td>
<td>0.50</td>
<td>0.35</td>
<td>0.122</td>
<td>0.94</td>
<td>88</td>
<td>0.19</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 4.1: LOWT conditions (Van der Werf, 2004).

In this table $T$ denotes the wave period, $u_{rms}$ the root mean square of the orbital velocity at the sandbed, $D_{50}$ the median grain diameter, $\Psi$ is the mobility number, which is the ratio of the disturbing force, defined by the square of the velocity amplitude $(A_1\omega)^2$ and the stabilising force due to gravity on the sediment defined by $(s - 1)gD_{50}$, and $c_r$ denotes the ripple migration speed.

A number of instruments was used in these experiments. First a Transverse Suction System (TSS) was used. This method is based upon a variety of suction samplers which collect sediment-fluid mixtures at 10 different heights above ripple crest and through. The water samples containing the suspended sand are collected in 10 buckets and the volume of the water is measured. The sand volume of each collected sample is measured using calibrated glass tubes and transferred to sand weight using the density and porosity of the sand. The actual concentration in the flow was determined by multiplying the measured concentration with a trapping efficiency coefficient $\alpha_s$. The value of $\alpha_s$ depends on many parameters, such as the nozzle dimension, its orientation to the flow, the velocities of intake and ambient flow, the sand particle characteristics (size and shape) and the relative density of the sand. The results of these measurements lead to time-averaged concentration profiles above the ripple crest and through.

Another instrument used is a new Bed profiler (BPS), developed by WL Delft Hydraulics. This instrument consists of a laser diode that sends out a laser sheet which is approximately 0.5 mm wide over the entire tunnel width, which is recorded by a camera. The output generated by the BPS is a 3-dimensional profile of the bed forms.
To determine the net transport rates, sediment traps are located at either end of the tunnel. The amount of sediment found in these traps after each test, together with BPS measurements of the bed levels before and after each test, was used to calculate the net transport rates using a mass conservation technique.

More information about the facility, instruments and data can be found in Van der Werf (2004).

### 4.2.2 AOFT experiments

This flow tunnel is 16 m long with a glass sided, 10 m long, rectangular test section of 0.75 m high and 0.3 m wide. A 0.25 m sand bed can be placed, leaving 0.5 m for flow. The water motion is generated by a piston which is, in contrast to the LOWT, horizontally connected to the test section. A more detailed description, including an outline, is given in Appendix B. Measurements were carried out for three tests, labelled MR5A, MR5B and MR5C. The conditions for these tests are outlined in Table 4.2.

<table>
<thead>
<tr>
<th>Test</th>
<th>$T$ (s)</th>
<th>$u_{rms}$ (ms$^{-1}$)</th>
<th>$D_{50}$ (mm)</th>
<th>$\eta$ (m)</th>
<th>$\lambda$ (m)</th>
<th>$\Psi$ (-)</th>
<th>$c_r$ (mm$s^{-1}$)</th>
<th>$B$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR5A</td>
<td>5.0</td>
<td>0.27</td>
<td>0.44</td>
<td>0.039</td>
<td>0.238</td>
<td>20</td>
<td>0.08-0.12</td>
<td>0.25</td>
</tr>
<tr>
<td>MR5B</td>
<td>5.0</td>
<td>0.44</td>
<td>0.44</td>
<td>0.076</td>
<td>0.408</td>
<td>54</td>
<td>0.31</td>
<td>0.25</td>
</tr>
<tr>
<td>MR5C</td>
<td>5.0</td>
<td>0.53</td>
<td>0.44</td>
<td>0.081</td>
<td>0.487</td>
<td>80</td>
<td>0.17-0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 4.2: AOFT conditions (Van Leeuwen, 2004).

To measure the concentration, two experimental set-ups were used. First a suction sampling set-up was used, this set-up is based on similar techniques as the TSS of the LOWT experiments. The second experimental set-up consisted of two different instruments for concentration measurements, an Optical Concentration meter (OPCON) and an Acoustic Backscatter System (ABS). The vertical elevation of the OPCON measurements were varied at six different positions above the bed. On the horizontal scale the measurements covered the entire ripple, because the ripples migrated entirely underneath the probes. The OPCON works by sending infrared light through the water column, which is received by a sensor. The decrease in light, which is picked up by a sensor, is an indication of the sediment concentration in suspension. The ABS makes use of high frequency sound which is transmitted and backscattered by the sediment in suspension. The received pulses are processed and lead to time-dependent suspended concentration profiles.

To determine the ripple dimensions, ripple migration rates and the bed levels below the instrument a Sand Ripple Profiler (SRP) was used. The SRP is a cylindrical instrument that is positioned above the bed. The instrument uses SONAR to determine the position of the bed. This means that sound is transmitted and the backscatter is received. The signal that is received by the computer linked to the SRP, consists of all the back scattered signals picked up by the SRP. Software is used to determine the strongest backscatter which represents the bed surface.

Sediment was collected in sand traps and a technique, identical to the one used in the LOWT experiments, was used to determine the net transport rates.
More information about the facility, instruments and data can be found in Van Leeuwen (2004), Van der Werf and Doucette (2005) and Van der Werf et al. (2005a).

4.3 Ripple predictions

Figure 4.1 shows the ratio of the predicted and measured ripple dimensions for the LOWT series. For clarity of the figure, a distinction is between the various experiments on the basis of $u_{\text{rms}}$. In Table 4.3 an overview is given of the measured and predicted ripple dimensions, and the corresponding steepness.

In Figure 4.1(a) it can be seen that the ripple predictions are accurate for $T=5\,\text{s}$, but when the wave period increases the ripple dimensions tend to get underestimated. There are minor differences between the predicted and measured steepness for these conditions, because both ripple height and ripple length are underestimated with approximately the same amount. In Figure 4.1(b) the same behaviour is noticeable. For a period of 5 s the ripple dimensions are predicted quite accurate, but for longer periods the ripple dimensions tend to get underestimated. Regarding the steepness, the same behaviour is also noticeable as in figure (a), only here the difference in steepness is much larger.

Figure 4.1: Comparison of the measured and predicted ripple dimensions for the LOWT experiments. Here 'stpn' denotes the ratio of the predicted and measured ripple steepness.

The ripple predictions of the AOFT experiments are given in Figure 4.2. For all three conditions the predicted ripple length overestimates the measured ripple length. This is especially the matter for the condition with the lowest $u_{\text{rms}}$ (MR5A), which has very small ripples. The measured steepness exceeds the imposed maximum steepness of 0.14 for all conditions, which explains why the ripple steepness is underestimated for all conditions. The predictions of the ripple height are the result of the maximum steepness, because the ripple height is adjusted to meet the requirement of the maximum steepness.

It can be concluded that the current method for predicting the ripple dimensions is not reliable for large ripple dimensions. Ripple dimensions are relatively more underestimated
4.4 Time-averaged concentration profiles

In this section time-averaged concentration profiles are compared with the measurements. For brevity, only the T4 series and the AOFT experiments are compared in this section. The results of the T5 series can be found in Appendix C.

Table 4.3: Measured and predicted ripple dimensions in cm. Here, 'p/m' stands for the ratio of the predicted and measured dimension in question.

<table>
<thead>
<tr>
<th>Test</th>
<th>( \eta_m )</th>
<th>( \eta_p )</th>
<th>p/m</th>
<th>( \lambda_m )</th>
<th>( \lambda_p )</th>
<th>p/m</th>
<th>( (\eta/\lambda)_m ) (-)</th>
<th>( (\eta/\lambda)_p ) (-)</th>
<th>p/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4-05</td>
<td>5.8</td>
<td>5.7</td>
<td>1.0</td>
<td>44</td>
<td>41</td>
<td>0.9</td>
<td>0.13</td>
<td>0.14</td>
<td>1.1</td>
</tr>
<tr>
<td>T4-07</td>
<td>8.6</td>
<td>4.7</td>
<td>0.5</td>
<td>62</td>
<td>33</td>
<td>0.5</td>
<td>0.14</td>
<td>0.14</td>
<td>1.0</td>
</tr>
<tr>
<td>T4-10</td>
<td>10.2</td>
<td>2.9</td>
<td>0.3</td>
<td>76</td>
<td>23</td>
<td>0.3</td>
<td>0.134</td>
<td>0.128</td>
<td>0.9</td>
</tr>
<tr>
<td>T5-05</td>
<td>5.1</td>
<td>5.4</td>
<td>1.1</td>
<td>46</td>
<td>38</td>
<td>0.8</td>
<td>0.11</td>
<td>0.14</td>
<td>1.3</td>
</tr>
<tr>
<td>T5-07</td>
<td>10.1</td>
<td>3.5</td>
<td>0.3</td>
<td>75</td>
<td>25.6</td>
<td>0.3</td>
<td>0.135</td>
<td>0.138</td>
<td>1.0</td>
</tr>
<tr>
<td>T5-10</td>
<td>12.2</td>
<td>2.0</td>
<td>0.2</td>
<td>94</td>
<td>19</td>
<td>0.2</td>
<td>0.13</td>
<td>0.105</td>
<td>0.8</td>
</tr>
<tr>
<td>MR5A</td>
<td>3.9</td>
<td>5.2</td>
<td>1.9</td>
<td>24</td>
<td>37</td>
<td>1.5</td>
<td>0.16</td>
<td>0.14</td>
<td>0.9</td>
</tr>
<tr>
<td>MR5B</td>
<td>7.6</td>
<td>7.2</td>
<td>0.9</td>
<td>41</td>
<td>51</td>
<td>1.3</td>
<td>0.19</td>
<td>0.14</td>
<td>0.8</td>
</tr>
<tr>
<td>MR5C</td>
<td>8.1</td>
<td>7.2</td>
<td>0.9</td>
<td>49</td>
<td>51</td>
<td>1.0</td>
<td>0.17</td>
<td>0.14</td>
<td>0.8</td>
</tr>
</tbody>
</table>
T4-05

The concentration profiles for series T4-05 are plotted in Figure 4.3 where Figure 4.3(a) contains the comparison of the measured data with the model outcomes in the case of imposed ripple dimensions and Figure 4.3(b) the results for the predicted ripple dimensions. Here \( z/\eta = 0 \) corresponds to the (undisturbed) mean bed level which means \( z/\eta = 0.5 \) corresponds to the ripple crest level. In Section 4.5 the \( C_0 \) values of the individual conditions will be discussed separately.

As can be seen from both figures the original 1DV model gives very good predictions of the concentration profile for this condition. The profile with use of the imposed ripple dimensions gives slightly lower concentrations than the 'predicted'. The vertical concentration gradient of both graphs shows good agreement with the measured data. A reason for the 'good' match in both cases could be that the conditions of this specific test are very similar to the conditions of the experiments used by Davies and Thorne (2004) for model calibration and validation. The two experiments used in their research had both a wave period of 5 s and a near bed orbital velocity of 0.33 ms\(^{-1}\) and 0.27 ms\(^{-1}\) respectively, which lie rather close to near bed orbital velocity of 0.40 ms\(^{-1}\), the \( D_50 \) of both their conditions was 0.33 mm, instead of 0.35 mm in this research. The slight differences that exist between both figures can be ascribed to the variations in reference concentration. The bed roughness \( (k_s) \) in both cases was almost equal, so the variations in mean eddy viscosity were negligible.

![Figure 4.3](image)

\( \eta = 5.8 \text{ cm} \quad \lambda = 44 \text{ cm} \quad \frac{\eta}{\lambda} = 0.13 \)  
\( \eta = 5.7 \text{ cm} \quad \lambda = 41 \text{ cm} \quad \frac{\eta}{\lambda} = 0.14 \)

**Figure 4.3:** Comparison of the measured and predicted concentration profiles for condition T4-05, for both imposed (a) and predicted (b) ripple dimensions.

T4-07

For this series the concentration profile for the 'imposed' condition (Figure 4.4(a)) is underestimated again, but slightly more compared to the T4-05 series. The concentration profile of the predicted case (Figure 4.4(b)) shows better agreement as it nearly matches the measured concentration profile. Despite the disagreement in the ripple dimensions, the ripple steepness is the same for both conditions, which leads to comparable estimations of the reference
4.4 Time-averaged concentration profiles

concentration for both conditions.

Figure 4.4: Comparison of the measured and predicted concentration profiles for condition T4-07, for both imposed (a) and predicted (b) ripple dimensions.

T4-10

For this experimental condition both ‘imposed’ (Figure 4.5(a)) and ‘predicted’ (Figure 4.5(b)) calculations lead to an underestimation of the measured concentration profile. The concentration gradient of the ‘imposed’ case is smaller than the measured concentration gradient. The calculated concentration gradient of the ‘predicted’ calculation agrees quite well with the measurements in the lower layer \(z/\eta \geq 2\), but shows more disagreement for the predictions in the upper layer, were the concentration gradient is stronger compared to the lower layer.

Figure 4.5: Comparison of the measured and predicted concentration profiles for condition T4-10, for both imposed (a) and predicted (b) ripple dimensions.
The reference concentration for the 'imposed' case is slightly higher than the reference concentration for the 'predicted' case, caused by the lower predicted ripple steepness compared to the imposed ripple steepness. The cause for the variation in concentration gradient at $z/\eta = 2$ (which is also the matter for T5-07 and T5-10, see Appendix D) lies probably in the turbulence-closure formulation which is used for the upper layer. In this research however, the focus is on the lower layer due to its importance in the rippled bed regime, so no detailed analysis in this upper region will be carried out.

**MR5A**

The 'imposed' concentration profile for this experimental condition can be found in Figure 4.6(a). The concentration profile is largely overestimated for this case. Besides this overestimation, the concentration gradient is stronger than the measured gradient. For the predicted ripple dimensions (Figure 4.6(b)) the concentration profile is still overestimated but less strong than in the 'imposed' case. For this case the concentration gradient is weaker and also shows better agreement with the measured concentration gradient. The overestimation of the concentration profiles in both cases is caused by the strong overestimation of the reference concentration. For the 'imposed' case where the ripple steepness is quite high, there is a very strong overestimation. The difference in measured and predicted reference concentration is reduced in Figure 4.6(b) where the ripple steepness is lower. Thus, it seems from this series that the reference concentration is too sensitive to changes in the ripple steepness.

A final remark has to be made regarding the measuring conditions. Because the sediment transport was bedload-dominated for this series, the suspended load existed of very low concentrations ($< 0.1$ g/l), which made it rather difficult to determine the correct weight of the suction samples. Therefore, the accuracy of this measurement is somewhat lower than the accuracy of the other concentration measurements in this research.

![Graphs](image)

**Figure 4.6:** Comparison of the measured and predicted concentration profiles for AOFT condition MR5A, figure (a) with the imposed ripple dimensions and figure (b) with the 'predicted' condition.
MR5B

As for the 'imposed' case of this experimental condition (Figure 4.7(a)) there is again a very large overestimation of the reference concentration, resulting in an overall overestimation of the concentration profile. The concentrations are increased compared to the MR5A series, due to the increase in \( C_0 \) caused by the increase in orbital velocity and the increase in ripple height and ripple steepness. The concentrations are still approximately 10 times larger than the measurements. The concentration gradient is also larger compared to the measured gradient. In Figure 4.7(b) where the ripple dimensions are predicted, the measured and predicted concentration profiles match closer. In the 'imposed' case the reference concentration was almost 40 g/l, but is reduced to approximately 6 g/l when the ripples are predicted. The concentration gradient is also reduced, because of the reduction in the mean eddy viscosity and sediment diffusivity, which is caused by the reduction in the ripple height.

![Graph](image)

Figure 4.7: Time-averaged concentration profiles for both the 'imposed' (a) and 'predicted' (b) ripple dimensions for condition MR5B.

MR5C

In Figure 4.8(a) the time averaged concentration profile for this series is given. The predicted reference concentration here is more than 40 g/l, which is approximately 20 times higher than the measured value for this case. The concentrations are larger throughout the entire water column compared to the measured profile, because the predicted concentration gradient is slightly stronger than the measured gradient. When the ripple predictor is used (Figure 4.8(b)), a reduction in the reference concentration occurs to approximately 17 g/l, caused by the reduction in ripple steepness compared to the measured steepness. The predicted concentration gradient of this case is slightly weaker than the 'imposed' gradient, resulting in a better match of the measured concentration gradient.
Figure 4.8: Comparison of cycle-averaged concentration profiles for the ‘imposed’ ripple dimensions (figure (a)) and the ‘predicted’ ripple dimensions (figure (b)) for condition MR5C.

4.5 Reference concentration

In the previous section it is shown that the adjusted \( \text{Wiberg and Harris (1994)} \) method is rather poor in predicting the accurate ripple dimensions. In this section, a comparison is made between the measured and predicted reference concentrations, because the ripple dimensions are of great influence on the estimation of the reference concentration. First of all, an estimation of the measured reference concentration is required, because measurements were only carried out at certain heights above the ripple crest level. This is done by fitting an exponential shaped profile through the lower measuring points \((z \leq 2\eta)\) (see Equation 4.1), where the eddy viscosity and the sediment diffusivity are assumed to be constant. Extrapolation of this curve to the ripple crest level leads to an estimation of the measured reference concentration. The values of both the measured and predicted reference concentrations can be found in Table 4.4.

<table>
<thead>
<tr>
<th>Test</th>
<th>( C_{0,\text{meas}} ) (g/l)</th>
<th>Ripples imposed</th>
<th>Ripples predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_0 ) (g/l)</td>
<td>( C_0 ) pred/meas</td>
<td>( C_0 ) (g/l)</td>
</tr>
<tr>
<td>T4-05</td>
<td>5.75</td>
<td>4.8</td>
<td>0.8</td>
</tr>
<tr>
<td>T4-07</td>
<td>5.32</td>
<td>4.2</td>
<td>0.8</td>
</tr>
<tr>
<td>T4-10</td>
<td>3.39</td>
<td>2.8</td>
<td>0.8</td>
</tr>
<tr>
<td>T5-05</td>
<td>14.27</td>
<td>7.9</td>
<td>0.6</td>
</tr>
<tr>
<td>T5-07</td>
<td>5.34</td>
<td>11.7</td>
<td>2.2</td>
</tr>
<tr>
<td>T5-10</td>
<td>4.57</td>
<td>8.0</td>
<td>1.7</td>
</tr>
<tr>
<td>MR5A</td>
<td>0.22</td>
<td>1.3</td>
<td>5.9</td>
</tr>
<tr>
<td>MR5B</td>
<td>2.12</td>
<td>38.3</td>
<td>18.1</td>
</tr>
<tr>
<td>MR5C</td>
<td>3.14</td>
<td>42.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table 4.4: Comparison of measured and predicted reference concentrations.
In Figure 4.9(a) the results are outlined for the LOWT conditions. The conditions are grouped by corresponding $u_{\text{rms}}$ for easy comparison with figures in the previous section. The closed symbols in this figure represent the same experimental conditions in case of predicted ripple dimensions. For the case of imposed ripple dimensions, the predicted reference concentration is slightly underestimated, but still accurate for $\theta \leq 0.35$. For the highest Shields parameters the difference between the measured and predicted reference concentration is much larger. Here no consistency exist between over- or underestimations.

The strong dependency of Nielsen’s method on the ripple steepness, follows from the closed symbols, which represent the conditions with predicted ripple dimensions. In the previous sections it is shown that, although there were large differences between the predicted and measured ripple dimensions, there were no extreme differences between the measured and predicted steepnesses. The maximum difference is hardly 30% (condition T505). The results in this section show that this (minor) increase in ripple steepness leads to an increase of the reference concentration of more then 150%!

Figure 4.9(b) shows the results of the AOFT conditions. The large overestimations of the reference concentration for these conditions, can be related to the high ripple steepness of these conditions (see Table 4.3). The strong reductions in $C_0$, when ripples are predicted, emphasise once again the over-dependency on the ripple steepness of the current method.

![Graphs showing comparison between measured and predicted concentrations for LOWT and AOFT conditions](image)

(a) LOWT, $D_{50} = 0.35$ mm  
(b) AOFT, $D_{50} = 0.44$ mm

**Figure 4.9:** Comparison of the measured and predicted reference concentration for the LOWT [a] and AOFT series [b] within the same $u_{\text{rms}}$ range in figure (a) the period decreases with increasing $\theta$. The closed symbols represent the outcomes for the same conditions in case of predicted ripple dimensions.

### 4.6 Vertical mixing length

Apart from the variations in reference concentration, the time-averaged predictions in Section 4.4 also show variations in the concentration gradient. To compare the measured and
predicted concentration gradients, the following profile, for the cycle-averaged sediment concentration in the lower layer is assumed:

\[ C(z) = C_0 e^{-\frac{z}{L_s}} \]  (4.1)

with \( L_s \) the vertical mixing length; the length at which the reference concentration is decreased with a factor \( e \). The value of \( L_s \) for the measured data is determined by making use of the same fitted exponential curve, that is used to determine the reference concentration. The model calculates the sediment concentration at restricted levels along the water column, therefore a (linear) curve was also interpolated along the predicted (logarithmic) concentration profiles in the lower layer, to determine the predicted value of \( L_s \).

In Figure 4.10(a) the results for the LOWT experiments are outlined. Again, the open symbols represent the results with imposed ripple dimensions, and the closed symbols the results with predicted ripple dimensions. In case of imposed ripple dimensions, the mixing length is predicted quite accurate, with a maximum difference of only 25%. However, when ripples are predicted these differences become much larger, with a maximum difference of 66%. The cause of these differences are the variations in roughness height (\( k_s \)), due to variations in ripple dimensions. The roughness height influences the mean eddy viscosity (Equation 2.11), which is related to the mean sediment diffusivity of Equation 2.14. In Table 4.5 it can be seen that these differences between the 'imposed' and 'predicted' results are closely related to the difference in roughness heights.

In Figure 4.10(b) the results for the AOFT experiments are outlined. For the imposed ripple dimensions (open symbols) the mixing lengths are predicted less accurately than for the LOWT experiments. It is interesting that these conditions are all overestimated with approximately the same factor. An exact reason for this overestimation cannot be given, but possibly the grain-size distribution plays a role. For the LOWT experiments the median grain diameter was determined with a geometric standard deviation, defined as \( \sigma_g = 0.5(D_{84}/D_{50} + D_{50}/D_{16}) \).
had a value of 1.2, and for the AOFT experiments the geometric standard deviation was approximately 1.4. Thus, it is likely that the 'real' $D_{50}$ of the suspended sediment is somewhat larger for the AOFT experiments, than the value that is used in this research, and in Chapter 3 it was already shown that only minor changes in the median grain diameter are of large influence on the net transport rates. The results with predicted ripple dimensions show slightly better agreement. As mentioned before, this is caused by the reduction of the roughness height, when ripples are predicted (see Table 4.5).

<table>
<thead>
<tr>
<th>Test</th>
<th>$L_{s,\text{mean}}$ (cm)</th>
<th>$k_s$ (cm)</th>
<th>$L_s$ (cm)</th>
<th>pred/meas</th>
<th>$k_s$ (cm)</th>
<th>$L_s$ (cm)</th>
<th>pred/meas</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4-05</td>
<td>6.70</td>
<td>19.1</td>
<td>6.61</td>
<td>0.99</td>
<td>20.1</td>
<td>6.68</td>
<td>1.00</td>
</tr>
<tr>
<td>T4-07</td>
<td>10.20</td>
<td>29.8</td>
<td>9.70</td>
<td>0.95</td>
<td>16.4</td>
<td>7.22</td>
<td>0.71</td>
</tr>
<tr>
<td>T4-10</td>
<td>13.00</td>
<td>34.2</td>
<td>11.45</td>
<td>0.88</td>
<td>9.4</td>
<td>6.15</td>
<td>0.47</td>
</tr>
<tr>
<td>T5-05</td>
<td>4.80</td>
<td>14.1</td>
<td>5.95</td>
<td>1.24</td>
<td>18.7</td>
<td>6.81</td>
<td>1.42</td>
</tr>
<tr>
<td>T5-07</td>
<td>15.80</td>
<td>34.0</td>
<td>12.78</td>
<td>0.81</td>
<td>12.1</td>
<td>8.36</td>
<td>0.53</td>
</tr>
<tr>
<td>T5-10</td>
<td>16.70</td>
<td>39.6</td>
<td>15.02</td>
<td>0.90</td>
<td>5.3</td>
<td>5.60</td>
<td>0.34</td>
</tr>
<tr>
<td>MR5A</td>
<td>2.93</td>
<td>16.0</td>
<td>2.21</td>
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<td>17.9</td>
<td>4.23</td>
<td>1.44</td>
</tr>
<tr>
<td>MR5B</td>
<td>6.69</td>
<td>35.4</td>
<td>10.08</td>
<td>1.51</td>
<td>25.1</td>
<td>9.43</td>
<td>1.41</td>
</tr>
<tr>
<td>MR5C</td>
<td>7.17</td>
<td>33.7</td>
<td>10.78</td>
<td>1.50</td>
<td>25.0</td>
<td>10.08</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Table 4.5: Comparison of measured and predicted vertical mixing lengths.

### 4.7 Time-dependent concentration profiles

Time-dependent concentration profiles are measured with the OPCON for test MR5B and MR5C, at various heights above the bed. During the measurements the entire ripple migrated underneath the probes, which made bed-averaging possible. In this analysis only the time-dependent measurements of test MR5B are used. These measurements are considered to be the most reliable, because the ripples were very consistent in time and space for this condition. In Figure 4.11 the results are shown for imposed ripple dimensions at various heights above the bed. Here, the left column shows the absolute concentrations and the right column the concentrations, normalised by the mean concentration at the respective height. A comparison of these results with the results in case of predicted ripple dimensions, and the velocity profile that corresponds to these profiles, are shown in Appendix D.

As was noticed in the previous sections, there is a large overestimation of the reference concentration, which results in an overestimation of the concentration at every height in the column. At the lowest level the difference between measured and predicted concentrations, when ripples are imposed, is approximately a factor 10. The overestimation of the concentration gradient, which is shown in the previous section, leads to even larger differences at higher levels. The difference at the lowest level is reduced to approximately a factor 2, when ripples are predicted. This difference also increases with increasing height.
For the following analyses of the various time-dependent processes, reference is made to the normalised profiles of Figure 4.11, which give better insight in the processes due to the absence of absolute differences. Although the model is able to produce the main concentration peak (caused by the ejected vortex at onshore flow reversal), the moment of peak occurrence differs from the data. The reason for this difference is that Davies and Thorne (2004) used the data of Thorne et al. (2003) to calibrate the model. Their data, and thus the model, shows peak near-bed concentrations just at flow reversal. In the figures it can be seen that this setting is still present, as the main peak occurs around $t/T = 0.4$, which corresponds to the moment of onshore-offshore flow reversal (Figure D.1 in Appendix D). However, from the experimental data used in this analysis, it follows that the main concentration peak occurs a while after onshore flow reversal (approximately $0.17T$ later). It also follows that the model is not capable of producing the correct relative magnitude of the the main concentration peak. As noted by Davies and Thorne (2004), this could be caused by insufficient time-variation in the pick-up function, due to the absence of asymmetry in the concentration gradient.

In the measurements at the lowest two levels, two smaller peaks are clearly visible before and after the main peak. The peak around $t/T \approx 0.75$ is due to the passage of the main suspension cloud generated on the lee-side of the next onshore ripple. The peak at $t/T \approx 0.3$ is associated with maximum onshore flow, which creates a near-bed plume of sediment that originates from the mobile layer on the offshore ripple flank, moves over the ripple crest and travels in the onshore direction. In the lowest level even two more (very small) peaks are visible. The one at $t/T \approx 0.15$ is caused by the ejected vortex at off-onshore flow reversal and the peak at $t/T \approx 0.95$ is due to the passage of the main vortex of the ripple located 2 ripple lengths onshore. More information about these time-dependent measurements can be found in Van der Werf et al. (2005b).

The current formulation of the pick-up function allows only two peaks to occur. Therefore, three of these peak cannot be modelled, at least not with the constraint of positiveness of the pick-up function. Phase-lags with increasing height are in accordance with the measurements, but the damping of the modelled peak with increasing height is to weak. Where the measured peak is almost diminished in the upper layer, the modelled peak is still almost equal in magnitude to the lowest peak.
Figure 4.11: Absolute (left-hand side) and normalised (right-hand side) time-dependent concentration profiles for test MR5B at various heights above the ripple crest level.
4.8 Net transport rates

Now that the individual performance of each element is analysed, it is important to see how well the net transport rates are predicted. From an engineering point of view, these are the most important outcomes of the model. The results for both the LOWT and AOFT experiments can be found in Table 4.6 and a comparison between the measured and predicted data is outlined in Figure 4.12.

For the LOWT experiments, the predicted net transport rates, in case of imposed ripples, show good agreement with the measured transport rates. Almost every condition (except for T405) falls within a factor two difference of the measured transport rate. Here a factor two is applied to determine the model accuracy, as it is a common used interval for judging predicted sediment transport rates (e.g. Davies et al. (2002)). When ripples are predicted, represented by the closed symbols in this figure, the results become less accurate for 4 out of 6 conditions. For most of the cases, the difference between the ‘ripple imposed’ and ‘ripple predicted’ transport rates can be related to the predictions of the reference concentration and mixing lengths. For example, a decrease from the ‘ripple imposed’ to ‘ripple predicted’ transport rate is caused by a decrease in reference concentration and mixing length. A decrease in the mixing length, indicates that less sediment is entrained in the water column and thus, less transport takes place.

In Figure 4.12(b) the predicted transport rates for the AOFT conditions are compared with the measured transport rates. Following the $C_0$ predictions of these experiments, the results are not surprising at all. However, it is strange that the transport rates of the first and third condition vary within the same order as the reference concentration, but the transport rate of the second condition is even a factor 2 more overestimated. Since the mixing lengths are almost equal for all three conditions, it is not possible to find an explanation for this result on the basis of the present analysis. The strong reduction in transport rates, when ripples are predicted, is also not surprising, because the same reduction is noticeable in the predictions of the reference concentration.

<table>
<thead>
<tr>
<th>Test</th>
<th>$q_m$</th>
<th>$q_p$</th>
<th>pred/meas</th>
<th>$q_p$</th>
<th>pred/meas</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4-05</td>
<td>-2.88E-05</td>
<td>-1.32E-05</td>
<td>0.46</td>
<td>-1.71E-05</td>
<td>0.59</td>
</tr>
<tr>
<td>T4-07</td>
<td>-1.77E-05</td>
<td>-1.70E-05</td>
<td>0.96</td>
<td>-1.17E-05</td>
<td>0.66</td>
</tr>
<tr>
<td>T4-10</td>
<td>-1.16E-05</td>
<td>-1.37E-05</td>
<td>1.18</td>
<td>-3.95E-06</td>
<td>0.34</td>
</tr>
<tr>
<td>T5-05</td>
<td>-3.63E-05</td>
<td>-2.58E-05</td>
<td>0.71</td>
<td>-6.95E-05</td>
<td>1.92</td>
</tr>
<tr>
<td>T5-07</td>
<td>-3.49E-05</td>
<td>-6.63E-05</td>
<td>1.90</td>
<td>-3.88E-05</td>
<td>1.11</td>
</tr>
<tr>
<td>T5-10</td>
<td>-3.85E-05</td>
<td>-5.51E-05</td>
<td>1.43</td>
<td>-3.85E-06</td>
<td>0.10</td>
</tr>
<tr>
<td>MR-5A</td>
<td>4.27E-07</td>
<td>-1.54E-06</td>
<td>-3.60</td>
<td>-7.68E-07</td>
<td>-1.80</td>
</tr>
<tr>
<td>MR-5B</td>
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<td>-2.19E-05</td>
<td>5.93</td>
</tr>
<tr>
<td>MR-5C</td>
<td>-1.40E-05</td>
<td>-1.99E-04</td>
<td>14.24</td>
<td>-7.06E-05</td>
<td>5.04</td>
</tr>
</tbody>
</table>

Table 4.6: Measured and predicted net total sediment transport rates (in m$^2$/s) for the case of imposed and predicted ripple dimensions.
From Table 4.6 it becomes clear that for condition MR5A the measured net transport direction was onshore and that the predicted transport was offshore directed. A possible explanation can be found in the transport calculations below the ripple crest level. The current model does not actually model the presence of a ripple in this region, but assumes the concentration here to be equal to $C_0$. This results, in combination with the onshore near-bed velocity, in a very small onshore transport component compared to the offshore transport component above the ripple crest level. In reality, bedload transport takes place in this region which (most of the time) causes the ripples to migrate in onshore direction, and leads (probably) to a much larger onshore transport component.

![Graph](image1.png)

**Figure 4.12:** Comparison of predicted and measured total net transport rates, for both imposed ripple dimensions (open symbols) and predicted ripple dimensions (closed symbols).

### 4.9 Conclusions

In this chapter the predictions of the original model are compared with full-scale wave tunnel measurements collected in the Large Oscillating Water Tunnel at WL/Delft Hydraulics and the Aberdeen Oscillatory Flow Tunnel at Aberdeen University Fluids Laboratory. Comparison is made of the time-averaged and time-dependent concentration profiles and four other elements, namely the adjusted Wiberg and Harris (1994) ripple prediction method, Nielsen’s (1986) method for predicting the reference concentration, the predictions of the mixing length and the most general output for practical use: the net transport rates.

Time-averaged concentration profiles with imposed ripple dimensions show good agreement for the LOWT conditions, but are overestimated with approximately a factor 10 for the AOFT conditions. These overestimations are caused by the overestimation of the reference concentration, which is overdependent on the high ripple steepness of the AOFT experiments ($\eta/\lambda > 0.14$). When ripples are predicted, the measured and predicted AOFT profiles match closer, which is caused by the reduction in the reference concentration, due to the constrained maximum ripple steepness of 0.14. Differences in concentration profiles between predicted and imposed ripple dimensions for the LOWT conditions are much smaller, since the measured ripple steepness for these experiments did not exceed the (apparently) critical value of 0.14.
For one condition time-dependent profiles are compared and it is shown that the current model is capable of producing two concentration peaks, which represent the ejected vortices at flow reversal. However, the phase-moment and magnitude of these peaks do not correspond with the measurements. The current formulation of the pick-up function is also not capable of producing additional concentration peaks, caused by vortices of adjacent ripples and maximum onshore flow.

The prediction of the ripple dimensions is only accurate for the smallest ripple dimensions. When measured ripple dimensions increase, the adjusted Wiberg and Harris (1994) prediction method strongly underestimates the measured ripple dimensions. The prediction of the ripple steepness for all series is quite accurate, which can be attributed to the imposed maximum steepness in the ripple predictor. Comparison of the measured and predicted reference concentrations for the LOWT experiments shows good agreement. However, for the AOFT experiments the reference concentration is extremely overestimated, due to the over-dependency of Nielsen’s (1986) formula on the high ripple steepness of all these conditions.

Predicted vertical mixing lengths, which are a measure for the vertical concentration gradients of the time-averaged concentration profiles, show good agreement with the measurements. When ripple dimensions are predicted, the agreement becomes worse, which is caused by the influence of the ripple-related roughness height on the mixing length.

The predicted transport rates for the LOWT experiments all fell within approximately a factor 2 of the measured transport rates. When ripples are predicted, the results become worse, caused by the incorrect predictions of the reference concentration. The direction of the net transport for these conditions is predicted correctly. For the AOFT experiments, agreement between measured and predicted transport rates is very poor, which is mostly caused by the overestimation of the reference concentration. Use of the ripple predictor leads to better results, mainly because the predictions of the reference concentration are better, but still the difference is a factor 5 for two out of three cases. The current model is not capable of producing a positive transport for one of the AOFT experiments.
Chapter 5

Model improvement

5.1 Introduction

From the previous chapter it followed that several aspects of the original model could be improved. The reference concentration is overestimated for most of the conditions, especially for steep ripple conditions and high orbital velocities. It was also shown that ripple predictions are only accurate for wave periods of 5s. When periods increase, the ripple dimensions are strongly underestimated, which leads to underestimations of, for instance the ripple-related roughness height and thus the cycle-mean eddy viscosity. Another conclusions was that with the model is not capable of producing onshore net transport rates, which is the matter for one of the experimental conditions. Comparison of model results with measure time-dependent concentration profiles showed that the model produces insufficient time-variation in the pick-up function and that the phase moment of main concentration peak is not in accordance with the measurements.

In this chapter an outline of the improvements regarding these aspects is given. First of all, new methods for predicting the reference concentration and the ripple dimensions will be given in Section 5.2 and Section 5.3 respectively. In Section 5.4 a new approach is described, to include an onshore transport component. In Section 5.5 several improvements are described, regarding the time-dependent processes. Each of these improvements will be introduced with a short motivation, in which the choice for that specific improvement is substantiated. Once these improvements are implemented in the model, an assessment of the new model is carried out in Section 5.6 based on the dataset of the previous chapter. Finally, Section 5.7 presents the results of validation of the new model with an independent dataset.

5.2 Reference concentration

5.2.1 Motivation

As concluded in the previous chapter the prediction of the reference concentration with the formula of Nielsen (1986) is highly sensitive to the (miscalculated) ripple steepness. Especially for the AOFT experiments this relation leads to large overestimations of the reference concentration. For the LOWT experiments the predictions were quite good for near bed orbital velocities of 0.40 m/s but showed larger variations for the 0.50 m/s cases, because ripple
dimensions also showed larger variations in this region. The ability of the Nielsen (1986) formula to overestimate the reference concentration was also shown by Van der Werf and Ribberink (2005).

To confirm the need for better predictions of the reference concentration, the measured $C_0$ values are imposed in the model (see Appendix E). This results for all conditions in better descriptions of the net transport rates, which emphasises the need for a new $C_0$ formula. Recently, such a formula is proposed by Van der Werf and Ribberink (2005), based on the formula of Bosman and Steetzel (1986). Van der Werf and Ribberink (2005) compared the formulas of Nielsen (1986), Bosman and Steetzel (1986) and Lee et al. (2004) with data of all sorts of wave conditions and concluded that the formula of Bosman and Steetzel (1986) gave the best $C_0$ predictions. Van der Werf and Ribberink included a grain-size effect and a wave-asymmetry effect, which resulted in even better predictions of the reference concentration. A detailed description of this new formula is given in the next section.

### 5.2.2 Van der Werf & Ribberink (2005)

Bosman and Steetzel (1986) performed experiments in the small oscillating water tunnel of WL|Delft Hydraulics with sinusoidal waves using sand with $D_{50}=0.22$ mm. They proposed the following relationship for the reference concentration at the averaged bed level:

$$C_0 = M_0 u_0^{3.5} T^2$$

with

$$M_0 = 3000 \text{kgs}^{5.5}/\text{m}^{6.5}$$

(5.1)

where $u_0$ is the peak orbital velocity for purely sinusoidal water motion and the value of $M_0$ corresponds to a $D_{50}$ of 0.22 mm. According to Van der Velden (1987) the reference concentration of Bosman and Steetzel (1986) is also applicable for different grain-sizes ($C_0 \sim 1/D_{50}^2$). Van der Werf and Ribberink (2005) included this relationship and proposed the following non-dimensional formulation for the reference concentration:

$$C_0 = K \Psi \chi^{1.75} D_*^{1.25}$$

(5.2)

with calibration constant $K$, wave period parameter $\chi$ and dimensionless grain-size $D_*:

$$\chi = \frac{D_{50}}{\Delta g T^2}$$

(5.3)

$$D_* = D_{50} \left( \frac{\Delta g}{\nu^2} \right)^{1/3}$$

(5.4)

Van der Werf and Ribberink assume that Equation (5.2) also holds for the individual excursions of an asymmetric oscillation, the crests and troughs. This means that the reference concentration can be calculated for a symmetrical wave, with wave period $2T_c$ based on the crest period ($T_c$) of the asymmetrical wave and for another symmetrical wave based on the trough period ($T_t$) with a wave period of $2T_t$. Both reference concentrations are then weight-averaged to determine the reference concentration for the individual asymmetric wave:

$$C_{0,as} = \frac{T_c}{T} C_c + \frac{T_t}{T} C_t$$

(5.5)
in which \( C_c \) and \( C_t \) represent the time-averaged concentration during the crest and trough period respectively. Equation 5.2 and 5.3 can now be rewritten to take the effect of wave asymmetry into account:

\[
C_0 = \frac{K}{D_1^{1.25}} \left( \frac{T_c}{T} \chi_c \Psi_c^{1.75} + \frac{T_t}{T} \chi_t \Psi_t^{1.75} \right)
\]

(5.6)

where \( \chi_c \) and \( \chi_t \) are computed with Equation 5.3 with \( T = 2T_c \) and \( T = 2T_t \) respectively and \( \Psi_c \) and \( \Psi_t \) are the mobility numbers under the wave crest and trough based on \( u_c \) and \( u_t \).

Van der Werf and Ribberink found a value for \( K \) of 23.8 based on various regular, symmetrical and asymmetrical as well as irregular, symmetrical and asymmetrical wave conditions. The source code of this new method can be found in Appendix H.

Figure 5.1 shows that the predictions of \( C_0 \) with the new formula show better agreement with the measured data than the predictions by Nielsen’s formula. Where only 33% falls within a factor 2, 67% within a factor 5 and 78% within a factor 10 with Nielsen’s method, the values are 56%, 100% and 100% respectively, for the new method by Van der Werf and Ribberink (2005).

![Figure 5.1: Comparison of measured (LOWT and AOFT experiments) and predicted reference concentrations. The solid line denotes perfect agreement, the dashed line a factor 2 difference, and the dotted line differences within a factor 5.](image-url)

5.3 Ripple predictions

5.3.1 Motivation

In Section 4.3 the non-iterative procedure for the Wiberg and Harris (1994) ripple predictor is discussed. It seemed here that the ripple predictions became less accurate for increasing wave periods. It is essential that a reliable method for ripple predictions is included in the 1DV model, because concentration profiles and thus transport rates are influenced by
these dimensions. First of all the ripple dimensions determine the roughness height $k_s$, which influences the mean eddy viscosity $K$ and mean sediment diffusivity $K_s$. Both these parameters are of influence on the concentration profiles and thus on the net sediment transport rate. Secondly, the ripple dimensions are also of influence on the determination of the net suspended transport, because it is determined by vertical integration of the product of the horizontally-averaged (over one ripple length) concentration and velocity, from the ripple crest level ($z = \frac{1}{2} \eta$) to the water level ($z = h$). Furthermore, the prediction of the ripple dimensions instead of imposition of the measured dimensions is essential from a coastal managers point of view, since they want to predict sediment transport rates without the need for (expensive) detailed data on bed geometry.

O’Donoghue and Clubb (2001) and O’Donoghue et al. (2005) compared several ripple prediction methods, including the Wiberg and Harris (1994) method. They concluded that the Wiberg and Harris (1994) method is unreliable for field-scale conditions, which is in accordance with the results of the assessment in this report. They recommended the method of Mogridge et al. (1994) for predicting ripple geometry in oscillating flow, especially for field-scale flow periods and amplitudes. In the next section a description of this method is given.

5.3.2 Ripple predictor of Mogridge et al. (1994)

Mogridge et al. (1994) developed a prediction method, based on an extensive set of laboratory and field data, where the maximum ripple length and height depend on the wave period parameter $\chi$. Mogridge et al. (1994) plotted the non-dimensional ripple length and height of the experimental data against the period parameter and fitted the following curves:

\[
\log(\lambda_{\text{max}}/D) = 13.373 - 13.722 \chi^{0.02054} \quad (5.7)
\]

\[
\log(\eta_{\text{max}}/D) = 8.542 - 10.822 \chi^{0.03967} \quad (5.8)
\]

When the maximum ripple dimensions are calculated, the corresponding orbital diameters can be determined according:

\[
d_{0,\lambda_{\text{max}}}/D = \frac{10^{13.373-13.722 \chi^{0.02054}}}{1.07 \chi^{0.05}} \quad (5.9)
\]

\[
d_{0,\eta_{\text{max}}}/D = 5.564 (\eta_0/D)^{1.05} \quad (5.10)
\]

Mogridge and Kamphuis (1972) described a set of ‘design curves’ in which the ripple dimensions (normalised by their maximum value) are plotted as a function of the (normalised) orbital diameter for specified values of the wave period parameter. These curves, in combination with the calculated maximum ripple dimensions and corresponding orbital diameter, can then be used to determine the actual ripple dimensions. The source code of this ripple prediction method can be found in Appendix [H].
5.3 Ripple predictions

Figure 5.2 shows that the predictions of the ripple height are better for the Mogridge et al. (1994) method (78% within a factor 1.5) than for the Wiberg and Harris (1994) method (56% within a factor 1.5). The predictions of the ripple length by Mogridge et al.'s method are even better, here 100% falls within a factor 1.5 difference. For Wiberg and Harris's method only 44% falls within this range.

![Figure 5.2: Comparison of measured (LOWT and AOFT experiments) and predicted ripple dimensions for Wiberg and Harris and Mogridge et al. prediction methods. In both figures the dashed lines indicate a factor 1.5 difference.](image)

In Figure 5.3 the steepness of both predictions methods is compared with the measured steepness. Here a closer interval of 25% is applied, because of the small natural range in steepness of vortex ripples. It can be seen that the ripple steepness is predicted less accurate with the Mogridge et al. method. For the Wiberg and Harris method 67% falls within the range and for the Mogridge et al. method only 33% falls within this range. However, it has to be noticed here that these outcomes are not as convincing as the figure suggests. The difference between the steepness predictions of both methods is that the steepness of Wiberg and Harris is restricted to maximum of 0.14. Would the same maximum be imposed in the method by Mogridge et al. (1994), then 78% would fall within a factor 1.25 difference of the measured steepness. The additional effect of this imposed steepness, is that 100% of the predicted ripple heights would fall within a factor 1.5 of the measured height (assuming the ripple height would be adjusted). However, in the current model this maximum steepness is not imposed, simply because the current Mogridge et al. (1994) method is validated for a wide range of conditions and ripple dimensions. Would such an adjustment be made to the maximum steepness, than it is not clear whether the method is still valid for the entire range of conditions it is validated with.
5.4 Bed-load

5.4.1 Motivation

In Chapter 4 it became clear that the original model is not capable of producing net transport rates in positive (onshore) direction, which is the matter for condition MR5A. Sediment transport over rippled beds is considered to have two components, suspended transport and transport due to ripple migration (Doucette and O’Donoghue, 2002). Traykovski et al. (1999) measured ripple migration and time-varying velocity and suspended sediment profiles at a site where the sand size is $D \approx 0.4 \text{ mm}$. The net suspended sediment transport was wave-dominated and was offshore directed while the ripple migration was onshore. They also found that bedload model calculations forced with measured wave velocities predict bedload sediment transport magnitude and direction consistent with observed ripple migration rates in the field. Clubb (2001) measured the on- and offshore related transport components and concluded that ripple migration is the main source of onshore transport. Hoekstra et al. (2004) compared the bed-load formula of Ribberink (1998) with measured transport rates due to ripple migration, based on the so called dune tracking technique. Hoekstra et al. (2004) concluded that transport due to ripple migration can be well described by Ribberink (1998)’s bedload formula, especially under moderate wave conditions.

5.4.2 Bedload formula of Ribberink (1998)

The formula of Ribberink (1998) is a quasi-steady bed-load transport model valid for steady unidirectional flows, oscillatory flows and oscillatory flows combined with net currents. The expression for the instantaneous, non-dimensional sediment transport rate reads:

$$ \Phi(t) = m \left( |\theta(t)'| - \theta_{cr} \right)^n \frac{\theta'(t)}{|\theta'(t)|} $$  \hspace{1cm} (5.11)

with $\theta_{cr}$ the critical Shields parameter as a function of the non-dimensional grain size $D_*$ of Equation 5.4. The coefficients $m$ and $n$ were found by curve fitting of experimental data. Ribberink found for a large data set of laboratory experiments for a wide range of conditions.
The bedload transport is calculated on the basis of the time-dependent grain-related Shields parameter, which is defined as follows:

$$\theta' = \frac{1/2 \rho f_w |u(t)| u(t)}{(\rho_s - \rho) g D_{50}}$$

(5.12)

with $u(t)$ the time-dependent free stream velocity and $f_w$ the wave friction factor according Equation 2.19. Ribberink (1998) uses an implicit relation ($k_s = \max(3D_{90}, D_{50}(1 + 6(\theta' - 1)))$) to determine the roughness height. However, Ribberink (1998) found that for waves and waves + currents in the low Shields regime ($\theta' \leq 1$) a reduction of the roughness to $k_s = D_{50}$ leads to better transport predictions. Important here is that the Shields parameter used for the bedload calculations differs from the Shields parameter that the model calculates. The model calculates the Shields parameter on the basis of the total shear stress of Equation 2.5. This assumption would relate the bedload transport to the ripple-related Shields parameter instead of the grain-related Shields parameter, and is therefore not used. In the new model the bedload is calculated according the grain-related Shields parameter of Equation 5.12. This results in (positive) onshore directed bedload transport under asymmetric waves, since the Shields parameter is instantaneously related to the orbital velocity. The implementation of this bedload transport formulation in the source code can be found in Appendix H.

5.5 Time-dependent concentration

5.5.1 Motivation

The time-dependent results in the previous chapter showed that the current pick-up formulation is not capable of producing enough time-variation in the time-dependent concentration profiles. Davies and Thorne (2004) mentioned that this underestimation in asymmetry between the concentration peaks, is caused by the absence of an asymmetric contribution in the assumed concentration gradient at crest level (the second term in the numerator of Equation 2.15). Additional asymmetry in the concentration gradient will lead to a larger difference in magnitude between the two concentration peaks. This will also lead to substantial differences in the amount of sediment that is transported in both directions.

Another point of interest is the phase moment of the peak concentration. Davies and Thorne (2004) found the peak concentration just after flow reversal, while the new measurements show a peak concentration somewhat later. An exact reason for these different observations cannot be given, but probably the (calibration of the) measuring instruments are the cause. An extra asymmetric component in the concentration gradient will also lead to a phase shift in the peak concentration, therefore the calibration of the phase angle ($\phi_c$) will be carried out after implementation of the additional asymmetry. The benchmark comparisons also show that mixing in the upper layer is too strong. A reduction in the sediment diffusivity in this layer will probably lead to less diffusion in this layer, which can be implemented by a the choice of $\zeta \leq 0.4$ in Equation 2.16. However, the concentrations in the upper layer are substantially lower (O($10^{-1}$ - $10^0$) g/l) compared to the lower layer (O($10^0$ - $10^1$) g/l), therefore the emphasis will, at least for now, be on the two other improvements.
5.5.2 Additional asymmetry

To include an additional asymmetric contribution to the concentration gradient, a second order Stokes profiles is assumed for simplicity. Thus, to the (fully described) second term in Equation 2.15 an extra component is added as follows:

\[
(1 + A_c e^{2i\phi_c} e^{2i\omega t} + B A_c e^{4i\phi_c} e^{4i\omega t} + c.c.)
\]  

(5.13)

for simplicity the contribution of the second term is related to the asymmetry of the velocity profile \((B)\) instead of the (more complex) asymmetry related to the eddy viscosity. Due to this dependency on the asymmetry parameter \(B\) the maximum amplitude \((A_c)\) increases with increasing wave asymmetry according \(A_c = 1/(1 - B)\). For symmetrical waves \((B = 0)\) the solution shifts to the original symmetrical part in Equation 2.15.

Figure 5.4 shows the influence of the additional asymmetry on the the concentration gradient and the time-dependent part of the pick-up function. The figure shows that the additional component indeed leads to more time-variation in both peaks of the pick-up formulation. The source code for the new pick-up function can be found in Appendix H.

![Figure 5.4](image-url)

Figure 5.4: Influence of additional asymmetry component on the time variation in the concentration gradient (a) and on the time-variation in the pick-up function (b).

5.5.3 Calibration phase angle

To get the phase moment of the main concentration peak in accordance with the measured concentration peak, the phase angle \(\phi_c\) is re-calibrated. Therefore, the phase difference between the moment of the measured and modelled concentration maximum (including the additional asymmetric term in the concentration gradient) at the lowest level \((z = 2.3 \text{ cm})\) is determined. This difference is 63°, which results in a phase difference of \(\phi_c = \varphi_1 - 33 \cdot (\pi/180)\). The results of this rescaled phase angle on the time-dependent concentration profiles are outlined in the next section.
5.6 Assessment

In the previous sections several improvements were outlined, which are all implemented in the original model, leading to a new 'improved' model. In this section the modelling results will be presented of this new model. Three scenarios, based on varying bed-load related roughness heights, are calculated in this model. As mentioned before, Ribberink (1998) suggested a bedload-related roughness height of $D_{50}$ in the lower shields regime, while Hoekstra et al. (2004) found good results with a bedload-related roughness height equal to $3D_{90}$. To take the sensitivity for this roughness height into account, transport rates are predicted with both these values as well as the, at least to some extend, intermediate value of $2.5D_{50}$. Time-dependent concentration profiles are not compared in this section for brevity, and secondly, beforehand it can already be said that these profiles are improved in general, because of the better predictions of the reference concentration with the new method. So in this section, only the time-dependent concentration profiles as well as the net sediment transport rates are outlined. In both cases the results are outlined in reference to the measurements and the benchmark results of the original model (as in Chapter 4).

5.6.1 Time-dependent concentration profiles

In Figure 5.5 the time-dependent profiles for condition MR5B are given. Here, absolute concentrations are plotted in the left column and in the right column the concentrations are normalised by the mean concentration at the respective height. A couple of things can be noticed from these figures. First of all, the absolute concentrations are generally decreased, which can be attributed to a better, but still overestimated, prediction of the reference concentration with the new method of Van der Werf and Ribberink (2005). Secondly, now referring to the normalised profiles, the magnitude and phase moment of the main concentration peak are in better agreement with the data than the predictions of the original model. However, the initial magnitude (at $z = 2.3$ cm) of the concentration peak is still not in agreement with the magnitude of the measured peak. At $z = 6.8$ cm the measured peak decreased so much, that the magnitude of the modelled peak is in accordance with the measured peak. However, above this height the modelled peak is larger in magnitude than the measured peak. Lastly, the smaller peak at $t/T = 0.3$ (caused by the offshore flow reversal) is still modelled at the incorrect phase moment. This is as expected, since the phase moment of the main peak is calibrated to agree with the measurements.

The other smaller peaks that are shown by the data, which are caused by vortices of adjacent ripples and maximum onshore flow are still not modelled with the new model. This is not surprising, since the adjustments in the time-dependent part of the pick-up function only included a (restricted) increase in asymmetry. However, these peaks are relatively small compared to the main concentration peak and are therefore of minor influence on the net transport rates.
Figure 5.5: Comparison of time-dependent concentration profiles for condition MR5B at certain heights above the ripple crest level.
5.6.2 Net transport rates

In this section the measured transport rates are compared with the predicted transport rates of the original model and the predicted transport rates of the improved model. The results, with a bedload related roughness height equal to $3D_{90}$, are presented in Figure 5.6 and the corresponding transport rates can be found in Table 5.1 in Appendix F. In Appendix G the results are also shown for a bedload roughness of $D_{50}$ and $2.5D_{50}$, respectively. The figures show a comparison between the measured and predicted transport rates ranging from onshore (positive values) to offshore (negative values). The axes have a log-scale, and are combined at $\pm10^{-7}$, since it is not possible to take the log of zero.

![Figure 5.6: Comparison of measured and predicted transport rates in m$^2$/s. The solid line denotes perfect agreement, the dashed line a factor two difference and the dash-dotted line a factor 5 difference. For the new model, the bedload calculation is based on $k_s = 3D_{90}$.

Regardless of which roughness height is taken, the improved model gives better transport predictions than the original model. However, the improved model is only capable of predicting an onshore transport for $k_s = 2.5D_{50}$ and $k_s = 3D_{90}$. Table 5.1 shows the performance of the different models expressed through the percentage where the factor between the predicted and measured transport is within a factor 2, 5 and 10. In case a formula predicted the wrong transport direction, it was assumed that this factor was infinitely large. The $R^2$ mentioned in Table 5.1 is an often used statistic term for determining goodness of fit. It is defined as the deviation within the observed data, divided by the deviation between the predicted and the observed data. The closer $R^2$ approaches 1, the better the fit. In this case, the difference in $R^2$ between the original and improved model is a good indication that the improved model is actually better in describing the net transport rates. Comparison within the new model shows
that a roughness height equal to $D_{50}$ gives the worst predictions. Since $R^2$ is an important parameter that indicates how well the processes are described, it can be concluded that the predictions with $k_s = 3D_{90}$ give the best results.

<table>
<thead>
<tr>
<th>model</th>
<th>factor 2 % within</th>
<th>factor 5 % within</th>
<th>factor 10 % within</th>
<th>direction % correct</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>44</td>
<td>56</td>
<td>78</td>
<td>89</td>
<td>0.09</td>
</tr>
<tr>
<td>New, $k_s = D_{50}$</td>
<td>67</td>
<td>78</td>
<td>89</td>
<td>89</td>
<td>0.39</td>
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<td>78</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.43</td>
</tr>
<tr>
<td>New, $k_s = 3D_{90}$</td>
<td>56</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.50</td>
</tr>
</tbody>
</table>

**Table 5.1:** Performance of the transport predictions of the original and new model.

In Table 4.1 in Appendix 4 the bedload transport rates are compared with the suspended transport rates. From this table follows that the fraction of bedload is increased in the new model. In the original model the average bedload fraction in the total transport is 18%. In the new model this average bedload fraction is increased to approximately 33% (for $k_s = 3D_{90}$).

### 5.7 Validation

To test the validity of the original model, the regular asymmetric conditions of Clubb (2001) and O’Donoghue et al. (2005) are used. Although more regular asymmetric conditions were generated during these experiments, only the conditions are used, which generated uniform 2-dimensional ripples. Under bimodal 2D, or 3-dimensional ripples, more complex transport processes occur. At this point, it would go too far to assume a 1DV approach is capable of capturing these processes. The validity of the new model is only tested on the basis of the most general, and from an engineering point of view, the most important output: the net sediment transport rates.

#### 5.7.1 Experimental conditions

The experimental data of both series is collected in the AOFT. All conditions are under strong asymmetric wave conditions. The conditions are given in Table 5.2. To determine the settling velocities of the suspended sediment, the method of Van Rijn (1993) is applied again, with a correction factor of 0.75. This factor is the same as for the AOFT calibration dataset, since the same sand was used in both experiments. For the R series of Table 5.2 this factor is also applied, since no data of the suspended material was available for these series.

#### 5.7.2 Results

In this section the net transport predictions of the validation series are compared with the measured transport rates. In Figure 5.7 the predictions with the new model (based on a bedload roughness equal to $3D_{90}$) are compared with the measurements. The predictions with the original model are also shown in this figure. In Appendix 5 the results are shown for a bedload roughness of $D_{50}$ and $2.5D_{50}$, respectively. The figures show that the transport predictions of the improved model are better than the original model predictions. Although, within the improved model range, large variations occur for the different roughness heights.
Table 5.2: Experimental conditions by Clubb (2001) (R series) and O’Donoghue et al. (2005) (M series).

Especially for low transport rates \((O(\pm 10^{-6}) \text{m}^2/\text{s})\) the contribution of the bedload transport becomes relatively larger, and influences the direction of the net transport.

![Figure 5.7: Comparison of measured and predicted transport rates. The solid line is perfect agreement, the dashed line a factor two difference and the dash-dotted line a factor 5 difference. For the new model, the bedload calculation is based on \(k_s = 3D_{90}\).](image)

Table 5.3 gives a representation of the performance of the different models. From the increase in \(R^2\) follows that the new model, regardless of which roughness height is taken, shows more consistency with the measurements that the original model. Comparison shows that a roughness height equal to \(3D_{90}\) gives the best overall results. Eventhough not necessarily more predictions fall within a factor 10 compared to the original model, the largest part of
the predictions do fall within a closer range of the measurements. This result emphasises that the new model with a bedload related roughness equal to $3D_{90}$, gives the best overall results.

<table>
<thead>
<tr>
<th>model</th>
<th>% within factor 2</th>
<th>% within factor 5</th>
<th>% within factor 10</th>
<th>% correct direction</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>13</td>
<td>63</td>
<td>88</td>
<td>88</td>
<td>0.48</td>
</tr>
<tr>
<td>New, $k_s = D_{50}$</td>
<td>38</td>
<td>63</td>
<td>63</td>
<td>75</td>
<td>0.69</td>
</tr>
<tr>
<td>New, $k_s = 2.5D_{50}$</td>
<td>38</td>
<td>63</td>
<td>75</td>
<td>75</td>
<td>0.70</td>
</tr>
<tr>
<td>New, $k_s = 3D_{90}$</td>
<td>38</td>
<td>88</td>
<td>88</td>
<td>88</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Table 5.3: Performance of the transport predictions of the original and new model.
Chapter 6

Discussion

1DV models are very schematised representations of reality, which indicates that many assumptions are made. Consequently, such assumptions are of influence on the output generated with these models. In this chapter, together with a discussion of the results, the possible effects of some of these assumptions are discussed.

Concentration profiles

The first point of this discussion regarding the time-dependent comparison is that only the measurements of one condition are used for this comparison. The predicted phase moment of the main concentration peak is calibrated based on this single measurement. It is likely that this phase moment is different for the various experimental conditions of this research. However, insufficient (reliable) time-dependent data forced the use of one fixed phase moment of the main concentration peak for all conditions.

Another point of discussion is the strong time-variation in the peaks and the total amount of peaks in the measured concentration profile. In the lower regions, the measurements show additional concentration peaks, caused by the ejected vortices of adjacent ripples and maximum onshore flow. With the current (second order) asymmetric formulations for the eddy viscosity and concentration gradient it is not possible to produce these strong time-variations and additional peaks. By increasing the amplitudes of the symmetrical components in the pick-up function, more time-variation can be generated, and even additional peaks can be simulated. However, these adjustments would lead to negative values of the eddy viscosity during moments of the wave cycle, which is mathematically possible, but not physically meaningful. Besides, considering the small magnitude of these peaks compared to the main concentration peak it is of less importance to model such peaks correctly.

Although the damping of the concentration with height is improved with the new pick-up formulation, it is still not in accordance with the measurements. This insufficient damping, can be related to an overestimation of the sediment diffusivity, especially in the upper levels. In the original and improved model, the sediment diffusivity is taken as four times the eddy viscosity in the lower layer, decreasing to unity in the upper layer. A reduction of this factor would lead to less sediment entrainment with height, and thus to a better fit of the concentration profile for this specific condition. However, there is no physical explanation why the sediment diffusivity is this large compared to the eddy viscosity, but Davies and
Thorne (2004) suggested that 2D or even 3D effects are the cause of this relationship. In this study it would go too far to judge this suggestion, and therefore the original relationship is also adopted in the improved model.

Bedload assumption

The net transport rates are in good agreement with the measured rates, although some points are fit for discussion. First of all the current method of bedload inclusion is questionable. In this research it is simply stated that all transport beneath the ripple crest level is caused by ripple migration and that transport due to ripple migration can be treated as bedload over a plane bed. These are both quite rough assumptions of course. In the first place it can be assumed that the presence of strongly concentrated vortices at both sides of the ripple crest level during a large part of the wave cycle, lead to some form of suspended transport. Secondly, the assumption that ripple migration can be represented by a bedload formula, is not justifiable for negative migration rates, as found for series T405 and T505. In the present study this assumption is nevertheless still adopted, since it is a simple manner to include transport associated with ripple migration, without the need of additional input parameters (such as the ripple migration rate).

The inclusion of the bedload component was, in first instance, to make the model capable of predicting positive net transport rates. This also resulted in positive transport rates for the calibration dataset. However, for the validation dataset still incorrect predictions of the transport rates occur. As mentioned before, since positive net transport rates are in the order of $O(10^{-6} - 10^{-7} \text{m}^2/\text{s})$ and the negative transport rates are in the order of $O(10^{-4} - 10^{-6} \text{m}^2/\text{s})$, the practical importance of the correct direction becomes less important. In coastal engineering, the determination of sand budgets are based upon transport gradients. Therefore it makes not a large difference whether such low transport rates are predicted in the wrong direction.

Grain size influence

The assessment of the original model showed that variations in grain size (and settling velocity) are of large influence on the predictions of the sediment transport rates. Although the improved model shows less dependency on the grain diameter (due to the new $C_0$ formulation), it still of influence on the transport predictions. First of all, there is uncertainty related to the estimation of the grain size and settling velocities for the experimental conditions. Since the measurements of grain sizes and settling velocities are based on estimations and empirical relations, there is still uncertainty concerning these values.

Another point of interest is the grain size distribution. For the calibration dataset, there are differences in the geometric standard deviations of the median grain-sizes of the LOWT and AOFT experiments, which imply differences in the grain-size distributions of these datasets. These variations in grain size lead to sorting processes near rippled beds, which are not included in the current model that only makes use of a single grain size in suspension.

The last important issue regarding the grain size is that for the AOFT validation dataset, the same suspended grain size/bed grain size ratio is used as for the AOFT calibration dataset.
Since it is unlikely that all these experiments had the same grain distribution, it may be expected that this estimation leads to some uncertainty of the transport predictions.

**Experimental conditions**

Although the influence of important model parameters are examined in this study, it still leaves the uncertainty in the measured data as an important source of influence. For instance, the measured transport rates of the LOWT series do not show a clear relationship with increasing mobility number. Van der Werf (2004) showed that these measurements had maximum possible errors of 30%, which are not taken into account in the present study. Since many other measurements (e.g. concentration, bedform) are accompanied by such errors, some caution has to be taken regarding the experimental conditions in this study. However, these errors are not so large that they cover the large variations between measured and predicted transport rates of, for instance, a factor 5.

**Model approach**

In the current approach it is assumed that the total stress is related to the velocity gradient by the eddy viscosity in analogy with molecular motion. It has often been pointed out that this assumption cannot be correct, because the "free paths" of the large eddies responsible for momentum transfer are not small compared with the fluid domain (e.g. Rodi [1984]). However, Davies and Villaret (1999) showed that this assumption in combination with the time-varying eddy viscosity is a good practical tool to characterise the vortex-shedding process.

Another matter is the importance of all the empirical formulations (e.g. reference concentration, ripple dimensions, mean eddy viscosity, bedload) on the model predictions, especially on the net transport rates. For instance, a frequently discussed parameter within these empirical formulations is the description of the roughness height. The assessment of the original model and the different bedload predictions of the improved model showed the sensitivity that is related to this parameter. However, from a practical point of view there is a need for the prediction of transport rates, based on as little input as possible. Therefore, together with the good results with imposition of the measured ripple dimensions and reference concentration, the main improvements regard these empirical elements of the model.
Chapter 7

Conclusions & Recommendations

7.1 Conclusions

What is the influence of the grain-size, wave asymmetry, orbital velocity and wave period on the net sediment transport as predicted by the original 1DV model?

Sensitivity on the predictions of the net transport is investigated for four different input parameters. It is shown that the model is most sensitive for variations in median grain diameter (and the related settling velocity) and the orbital velocity. Both these parameters have strong influence on the prediction of the reference concentration, which determines the amount of sediment pick-up during each wave cycle, and thus influences the transport rates. Variations in the grain diameter of 10\% lead to variations in the predicted transport rates of 30-40\%, while variations in the orbital velocity of 10\% lead to very large variations in the net transport rates of approximately 100\%. Changes in asymmetry are only of influence for low asymmetry parameters ($B \leq 0.1$). When asymmetry further increases to its maximum value ($0.1 < B \leq 0.25$), the transport rates remains constant. Variations in the wave period are also of minor influence on the net transport rates. Especially in the most important (field) regime for this research ($T \geq 4$ s), variations in $T$ of 10\% only lead to variations in the net transport of approximately 5\%.

How does the original 1DV model compare with the measured ripple dimensions, time-averaged and time-dependent concentrations and net sediment transport rates?

The model is compared with nine different full-scale regular asymmetric wave experiments, carried out in the Aberdeen Oscillatory Flow Tunnel (AOFT) at the University of Aberdeen Fluids Laboratory and the Large Oscillating Wave Tunnel (LOWT) at WL|Delft Hydraulics. Time-averaged concentration profiles of the LOWT experiments show good agreement with the model predictions, but the AOFT profiles are all overestimated with approximately a factor 10. Comparison of model outcomes with time-dependent concentration profiles, showed that the model is capable of producing two concentration peaks, which represent the ejected vortices at on- and offshore flow reversal. However, the phase moment and magnitude of these peaks are not in accordance with the measured data. The measurements also show smaller concentration peaks, caused by the ejected vortices of adjacent ripples and maximum onshore flow. However, these peaks cannot be modelled with the current model. The prediction of
the reference concentration according to Nielsen (1986) is not valid in steep ripple regimes \((\eta/\lambda > 0.14)\), where it extremely overestimates the measured concentrations. Consequently, net transport rates are also largely overestimated in these regions. Although the model does predict the correct (offshore) direction for eight out of nine conditions, it is not capable of producing an onshore net transport for one condition. To predict the ripple dimensions in the original model, an adjusted version of the Wiberg and Harris (1994) formulation is used. Comparison with measured ripple dimensions showed that this formulation is not capable of predicting large ripple dimensions \((\eta \geq 7 \text{ cm} \text{ and } \lambda \geq 50 \text{ cm})\).

How can the original model be improved?

Four major improvements were made to the original model. First of all, the ripple prediction method of Mogridge et al. (1994) is implemented to replace the adjusted method of Wiberg and Harris (1994). Comparison of both methods shows that the predicted ripple dimensions by Mogridge et al. (1994) show best agreement with the measurements, although the prediction of the ripple steepness is not necessarily improved. Secondly, since the predicted values of the reference concentration were rather poor with the original model, a new method by Van der Werf and Ribberink (2005) is implemented to replace the method of Nielsen (1986). This new method gives better descriptions of the reference concentration for a substantial number of cases. As third improvement, bedload transport according to Ribberink (1998) is added to the predicted net suspended transport. This approach leads in general to larger onshore transport components compared to the original model, and results in better predictions of the net total transport rates. However, no improvements were made regarding the direction of the net total transport rates. The last improvement regards the time-dependency in the pick-up function. An extra asymmetric component is added in this function to generate more time-variation in the suspended sediment profiles. The results show that the improved model generates more time-variation in the concentration profile than the original model, which corresponds better with the measurements. However, with the current formulation of the pick-up function this is also the maximum time-variation that can be generated, which is not enough compared to the measurements.

Regarding the net transport predictions, the improved model gives significantly better results than the original model. However, the choice of a specific bedload-related roughness height is of strong influence on the prediction of onshore net transport rates. Comparison of predicted and measured transport rates shows the importance of the onshore transport component for low transports. Consequently, for high measured transport rates the onshore component does not play a role in the prediction of the correct direction, but it does lead to better results. Best results are found with a bedload-related roughness height equal to \(3D_{90}\).

Does the improved model give better predictions of net transport rates, measured during other, independent experiments, than the original 1DV model?

Validation of the improved model is carried out with an independent dataset of eight different full-scale wave tunnel conditions, under regular asymmetric waves. The validation confirms that the improved model gives better predictions of the net transport rates, although the predictions of the correct direction are not necessarily improved. The best overall results of the improved model are found with a bedload related roughness height equal to \(3D_{90}\).
7.2 Recommendations

Although the present model shows a promising, computationally inexpensive method to describe sand transport processes over rippled bed, there are still some recommendations for further research.

First of all the research can be extended with a comparison of the model results with the flow data that is collected during the AOFT experiments. Detailed time-dependent flow measurements were carried out, which can contribute to model validation and calibration. Consequently, comparison of time-averaged and time-dependant sediment fluxes can also be carried out.

The model results can be put in a broader perspective by comparison of the results of this model, with the results of other sand transport models for rippled beds.

Higher-order solutions of the time-variation in the eddy viscosity and concentration gradient can lead to more time-variation and thus to more agreement with measured time-dependent concentration profiles.

Comparison with more time-dependent concentration measurements is needed, to gain more insight in the phase difference between moment of flow reversal and the suspended cloud ejection.

Following the experimental tunnel conditions of this research, the model results can be compared with, for instance flume or field measurements to check the validity of the model in such conditions.

Sand transport models are generally part of more complex models that predict the morphological behaviour of a coastal system over large temporal and spatial scales. Therefore, within the framework of this project, it can be considered to implement the current model (approach) in models that predict the morphological behaviour of large-scale sand mining pits / areas.

The model can also be used to extend existing sand budget studies. The models used in these studies generally predict (wave-induced) sand transport in the direction of (asymmetric) wave propagation. However, this research shows that wave-induced transport rates over rippled beds are generally offshore directed. Since ripples cover the largest part of the shoreface it is important to include these transport processes, which can be achieved with the current model.
Bibliography


## Appendix A

### Model input

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<th>Parameter</th>
<th>Unity</th>
<th>Description</th>
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<td>Viscosity</td>
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<td>The kinematic viscosity of water, which amounts 0.01 cm²/s at 20°C.</td>
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<td>cm</td>
<td>The water depth, measured from the surface till the mean bed level.</td>
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<td>Depth average current</td>
<td>cm/s</td>
<td>When not present, the slightest current of 0.01 cm/s has to be imposed for numerical reasons.</td>
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<tr>
<td>Angle of wave attack on current</td>
<td>°</td>
<td>The smallest angle between wave and current direction.</td>
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<tr>
<td>Near-bed wave velocity amplitude</td>
<td>cm/s</td>
<td>The amplitude of the first term in the second order Stokes solution ($u_1$).</td>
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<td>Wave period</td>
<td>s</td>
<td>The period of the regular wave.</td>
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<td>Median sediment diameter</td>
<td>cm</td>
<td>The median grain diameter ($D_{50}$) of the bed material.</td>
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<td>Settling velocity</td>
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<td>The measured settling velocity of the suspended sediment.</td>
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<td>Ripple dimensions</td>
<td>cm</td>
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</tr>
<tr>
<td>Number of cycles</td>
<td>(-)</td>
<td>The number of wave cycles which are used in the simulations. The amount of wave cycles influences the phase-averaged components.</td>
</tr>
<tr>
<td>Current</td>
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<td>The mean current that can be imposed at a certain height above the bed, in this research only the wave-induced sediment transport examined, so no such current is present.</td>
</tr>
<tr>
<td>Near-bed velocity amplitude</td>
<td>cm/s</td>
<td>This is the amplitude of the second term ($u_2$) in the second order Stokes solution in.</td>
</tr>
</tbody>
</table>

*Table A.1: Necessary input parameters to run the 1DV model.*
Appendix B

Experimental facilities

LOWT

The LOWT basically consist of a vertical U-tube with one open leg. The other leg is provided with a piston which can generate regular and irregular wave conditions. These waves can be symmetrical as well as asymmetrical. The test section has a length of 14 m, a height of 1.1 m and a width of 0.3 m. The tunnel is designed to place a sediment bed of 0.3 m, leaving the upper 0.8 m for the oscillating flow. The following wave characteristics can be generated; wave periods up to 15.0 s and amplitudes of the orbital velocities in the range of 0.2-1.8 ms\(^{-1}\). To collect the sand that is eroded from the bed, two sand traps are placed underneath each cylinder.

![Diagram of the LOWT](image)

Figure B.1: The Large Oscillating Water Tunnel (Van der Werf, 2004).
AOFT

The AOFT has a total length of 16 m, with a 10 m long test section, which has a height of 0.75 m and a width of 0.3 m. A sand bed of 0.25 m can be placed in the test section, which results in flow depth of 0.5 m. The wave motion is generated with a piston, which is placed in the longitudinal direction of the flow. Waves with a minimal period of 5 s and a maximum amplitude of the orbital velocity of 1.5 m can be generated. Waves can be regular and irregular as well as symmetric and asymmetric.

![Diagram of the Aberdeen Oscillating Flow Tunnel](image).

**Figure B.2:** The Aberdeen Oscillating Flow Tunnel (Clubb, 2001).
Appendix C

Time-averaged concentration profiles

T5-05

For this series the ‘imposed’ case (Figure C.1(a)) also gives an underestimation of the reference concentration, which results in an overall underestimation of the concentration profile. In Figure C.1(b) where ripples are predicted, the concentration profile is overestimated with approximately a factor 2. The predicted reference concentration for the ‘imposed’ case equals 7.91 g/l and 19.60 g/l for the ‘predicted’ case. This differences between both cases are caused by the overestimation of the ripple steepness, which leads to a higher reference concentration and a larger eddy viscosity. The difference in this parameter is even more increased by the overestimated ripple height.

![Graphs showing concentration profiles](image)

**Figure C.1:** Comparison of the measured and predicted concentration profiles for condition T5-05, for both imposed [a] and predicted [b] ripple dimensions.
T5-07

For this experimental condition the concentration profiles are overestimated for both cases. Furthermore, the calculated concentration gradient in Figure C.2(a) is too small and shows less agreement with the measured data than the calculated concentration gradient in Figure C.2(b). The reference concentration for the 'imposed' case equals 11.7 g/l, while the reference concentration for the 'predicted' case is slightly higher with 12.9 g/l due to the minor difference in ripple steepness.

Important here is that for the case of the 'predicted' ripple dimensions the value of $A_1/k_s$ exceeds the maximum of 5.0 which is the boundary condition for Equation 2.11. This high value is caused by the underestimation of the ripple height which leads to a low value of the roughness parameter $k_s$. The result is that the use of the ripple predictor actually makes the model inapplicable for this condition.

![Figure C.2: Comparison of the measured and predicted concentration profiles for condition T5-07, for both imposed (a) and predicted (b) ripple dimensions.](image)

(a) $\eta = 10.1$ cm $\lambda = 75$ cm $\frac{\eta}{\lambda} = 0.135$

(b) $\eta = 3.5$ cm $\lambda = 25.6$ cm $\frac{\eta}{\lambda} = 0.138$
T5-10

Figure C.3(a) shows the concentration profile in case of imposed ripple dimensions. In the lower layer this profile is overestimated, but due to the weaker predicted concentration gradient compared to the measured gradient, the differences between the measured and predicted concentration becomes less with increasing height. In Figure C.3(b) where the ripple dimensions are predicted, the concentrations are underestimated. In this graph the differences become larger, caused by the smaller concentration gradient compared to the measured gradient.

The reference concentration here is 7.98 g/l for the ‘imposed’ case and for the ‘predicted’ case it is only 2.92 g/l. Again this difference is caused by the difference between the predicted and measured ripple steepness. As for the previous condition (T410), the course of the graph becomes steeper in the upper layer for corresponding reasons. Except for the $A_1/k_u$ ratio that is exceeded, there is also the influence of the low steepness of 0.105 on the reference concentration.

Figure C.3: Comparison of the measured and predicted concentration profiles for condition T5-10, for both imposed (a) and predicted (b) ripple dimensions.
Appendix D

Time-dependent concentration profiles

The time-dependent concentration profiles were gathered with the OPCON instrument. In this analysis only the results of test MR5B are used. The measurements for test MR5C were unreliable due to variations in the ripple dimensions and shape. The OPCON was positioned at five different heights above the ripple crest level. The lowest measurement, which took place under the ripple crest level, is left out because the model is not able to predict the right concentrations at this level. On horizontal scale the measurements covered the entire ripple, which made ripple-averaging possible. For clarity a schematisation of the corresponding velocity profile is given in Figure D.1. Note that the scale on the y-axis is different for both sides in Figure D.2. The first four heights correspond to the lower vortex-dominated layer of the model and the fifth height lies in the upper layer of the model.

Figure D.1: Velocity profile.
Figure D.2: Time-dependent concentration profiles for series MR5B at different heights above the ripple crest, the results for the imposed ripple dimensions are outlined at the left-hand side and the results for the predicted ripple dimensions at the right-hand side.
Figure D.3: Time-dependent normalised concentration profiles for series MR5B at different heights above the ripple crest, the results for the imposed ripple dimensions are outlined at the left-hand side and results for the predicted ripple dimensions at the right-hand side.
Appendix E

Imposed reference concentration

Figure E.1: Comparison of the computed (dimensionless) net total transport rates with the measured (dimensionless) net transport rates for both experimental series. Two different computations are compared, the first with Nielsen's reference concentration and in the second case the measured reference concentrations are imposed.
Appendix F

Net transport rates

In Table F.1 the model predictions of the net sediment transport rates are compared with the measured net transport rates of the calibration dataset (Van der Werf (2004) (T series), Van Leeuwen (2004) (M series)). Figure F.1 and F.2 the measured net transport rates are compared with the model predictions based on a bedload-related roughness height of $D_{50}$ and $2.5D_{50}$, respectively.

In Table F.2 the model predictions of the net sediment transport rates are compared with the measured net transport rates of the validation dataset (Clubb (2001) (R series), O’Donoghue et al. (2005) (M series)). Figure F.3 and F.4 the measured net transport rates are compared with the model predictions based on a bedload-related roughness height of $D_{50}$ and $2.5D_{50}$, respectively. It has to be noticed that for the new model with $k_s = D_{50}$, the result for condition MR10 is left out, since it underestimates the measured transport (and direction) with approximately a factor 100 (see Table F.2).
<table>
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Table F.1: Comparison of measured and predicted net transport rates in m$^2$/s for the calibration dataset.

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Table F.2: Comparison of measured and predicted net transport rates in m$^2$/s for the validation dataset.
Figure F.1: Comparison of measured and predicted transport rates in m²/s. The solid line denotes perfect agreement, the dashed line a factor two difference and the dash-dotted line a factor 5 difference. For the new model, the bedload calculation is based on $k_s = D_{50}$.

Figure F.2: Comparison of measured and predicted transport rates in m²/s. The solid line denotes perfect agreement, the dashed line a factor two difference and the dash-dotted line a factor 5 difference. For the new model, the bedload calculation is based on $k_s = 2.5D_{50}$. 
Figure F.3: Comparison of measured and predicted transport rates. The solid line is perfect agreement, the dashed line a factor two difference and the dash-dotted line a factor 5 difference. For the new model, the bedload calculation is based on $k_s = D_{50}$.

Figure F.4: Comparison of measured and predicted transport rates. The solid line is perfect agreement, the dashed line a factor two difference and the dash-dotted line a factor 5 difference. For the new model, the bedload calculation is based on $k_s = 2.5D_{50}$. 
Appendix G

Bedload transport rates
Table G.1: Bedload versus suspended transport rates for the calibration dataset.

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<td>-4.6</td>
<td>1.14E-05</td>
<td>-6.0</td>
<td>1.72E-05</td>
<td>-4.0</td>
<td>2.17E-05</td>
<td>-3.2</td>
<td></td>
</tr>
<tr>
<td>T507</td>
<td>-4.84E-05</td>
<td>1.12E-05</td>
<td>-4.3</td>
<td>9.71E-06</td>
<td>-5.0</td>
<td>1.42E-05</td>
<td>-3.4</td>
<td>1.76E-05</td>
<td>-2.7</td>
<td></td>
</tr>
<tr>
<td>T510</td>
<td>-3.77E-05</td>
<td>9.38E-06</td>
<td>-4.0</td>
<td>8.73E-06</td>
<td>-4.3</td>
<td>1.25E-05</td>
<td>-3.0</td>
<td>1.54E-05</td>
<td>-2.5</td>
<td></td>
</tr>
<tr>
<td>MR5A</td>
<td>-2.54E-06</td>
<td>4.54E-07</td>
<td>-5.6</td>
<td>1.84E-06</td>
<td>-1.4</td>
<td>3.12E-06</td>
<td>-0.8</td>
<td>4.51E-06</td>
<td>-0.6</td>
<td></td>
</tr>
<tr>
<td>MR5B</td>
<td>-2.79E-05</td>
<td>6.28E-06</td>
<td>-4.4</td>
<td>8.26E-06</td>
<td>-3.4</td>
<td>1.29E-05</td>
<td>-2.2</td>
<td>1.77E-05</td>
<td>-1.6</td>
<td></td>
</tr>
<tr>
<td>MR5C</td>
<td>-6.25E-05</td>
<td>1.46E-05</td>
<td>-4.3</td>
<td>1.43E-05</td>
<td>-4.4</td>
<td>2.19E-05</td>
<td>-2.9</td>
<td>2.97E-05</td>
<td>-2.1</td>
<td></td>
</tr>
</tbody>
</table>

Table G.2: Bedload versus suspended transport rates for the validation dataset.

<table>
<thead>
<tr>
<th>Test</th>
<th>$q_s$ (m$^2$/s)</th>
<th>$q_b$ (m$^2$/s)</th>
<th>$q_s/q_b$</th>
<th>$k_s = D_{50}$</th>
<th>$q_b$ (m$^2$/s)</th>
<th>$q_s/q_b$</th>
<th>$q_b$ (m$^2$/s)</th>
<th>$q_s/q_b$</th>
<th>$q_b$ (m$^2$/s)</th>
<th>$q_s/q_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR3</td>
<td>-7.01E-06</td>
<td>1.20E-06</td>
<td>-5.9</td>
<td>3.35E-06</td>
<td>-2.1</td>
<td>5.76E-06</td>
<td>-1.2</td>
<td>8.45E-06</td>
<td>-0.8</td>
<td></td>
</tr>
<tr>
<td>MR4</td>
<td>-1.25E-05</td>
<td>2.50E-06</td>
<td>-5.0</td>
<td>4.83E-06</td>
<td>-2.6</td>
<td>7.88E-06</td>
<td>-1.6</td>
<td>1.12E-05</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td>MR7</td>
<td>-1.30E-05</td>
<td>3.29E-06</td>
<td>-4.0</td>
<td>5.24E-06</td>
<td>-2.5</td>
<td>8.02E-06</td>
<td>-1.6</td>
<td>1.09E-05</td>
<td>-1.2</td>
<td></td>
</tr>
<tr>
<td>MR10</td>
<td>-1.28E-06</td>
<td>2.84E-07</td>
<td>-4.5</td>
<td>1.29E-06</td>
<td>-1.0</td>
<td>2.10E-06</td>
<td>-0.6</td>
<td>2.93E-06</td>
<td>-0.4</td>
<td></td>
</tr>
<tr>
<td>RR3A</td>
<td>-6.29E-05</td>
<td>1.52E-05</td>
<td>-4.1</td>
<td>1.06E-05</td>
<td>-5.9</td>
<td>1.59E-05</td>
<td>-3.9</td>
<td>2.29E-05</td>
<td>-2.7</td>
<td></td>
</tr>
<tr>
<td>R4a</td>
<td>-8.97E-05</td>
<td>2.22E-05</td>
<td>-4.0</td>
<td>1.37E-05</td>
<td>-6.5</td>
<td>2.05E-05</td>
<td>-4.4</td>
<td>2.93E-05</td>
<td>-3.1</td>
<td></td>
</tr>
<tr>
<td>RR10a</td>
<td>-1.03E-05</td>
<td>2.78E-06</td>
<td>-3.7</td>
<td>3.66E-06</td>
<td>-2.8</td>
<td>5.40E-06</td>
<td>-1.9</td>
<td>7.61E-06</td>
<td>-1.4</td>
<td></td>
</tr>
<tr>
<td>R11a</td>
<td>-3.38E-05</td>
<td>9.62E-06</td>
<td>-3.5</td>
<td>8.10E-06</td>
<td>-4.2</td>
<td>1.16E-05</td>
<td>-2.9</td>
<td>1.60E-05</td>
<td>-2.1</td>
<td></td>
</tr>
</tbody>
</table>
Appendix H

FORTRAN77 source code

Input file

Input file *rippled1a_input.dat* for the new model. In comparison with the original input file, changes are made to line 10 and 11, where it now is possible to choose between various methods.

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>Viscosity, cm(^2)/s</td>
<td>0.01</td>
</tr>
<tr>
<td>80</td>
<td>Water depth, cm</td>
<td>80</td>
</tr>
<tr>
<td>0.01</td>
<td>Depth-averaged current, cm/s</td>
<td>0.01</td>
</tr>
<tr>
<td>0</td>
<td>Angle of wave attack on current, deg</td>
<td>0</td>
</tr>
<tr>
<td>68.6</td>
<td>Near-bed wave velocity amplitude (U1), cm/s</td>
<td>68.6</td>
</tr>
<tr>
<td>10.0</td>
<td>Wave period, s</td>
<td>10.0</td>
</tr>
<tr>
<td>0.035</td>
<td>Median diameter D50 of bed sediment, cm</td>
<td>0.035</td>
</tr>
<tr>
<td>4.3</td>
<td>Settling velocity of suspended sediment, cm/s</td>
<td>4.3</td>
</tr>
<tr>
<td>17.15</td>
<td>Near-bed velocity amplitude (U2), cm/s</td>
<td>17.15</td>
</tr>
<tr>
<td>1</td>
<td>0 0 0  0=Wiberg Harris, 1=Mogridge, 2=impose; ripple length, cm; height, cm</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0 0  [Ref. conc. method, 0=Nielsen, 1=Werf, 2=impose; ref. conc., g/l]</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>Turbulence damping by sediment, Yes = 1, No = 0</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>Number of cycles in run: e.g. 60,240,480,19920,38400</td>
<td>1000</td>
</tr>
<tr>
<td>0</td>
<td>Current u (cm/s) given at height z. For no such input = 0</td>
<td>0</td>
</tr>
</tbody>
</table>

Source code

The following lines in the new model (*rippled1a.for*) are adjusted/added compared to the original model. A subdivision is made regarding the various improvements of Chapter 5.

General

```
99   CALL HYDRAULIC(RHEI,RLEN,Z0,CREST,
100   : U0,V0,WSET,ubard0,period,d50,d,anlgs,Usnd,VIS,
```
Pick-up function

** Ac value adjusted in combination with asymmetric concentration gradient (April 2005)

**

\[ Ac = \frac{1}{1 - \text{asym}} \]

Symmetrical case: -33.48 deg lead gives coincidence of peak eddy visc and conc

\[ \text{phiconc} = \text{phieddy} - 33.48 \times \frac{\pi}{180} \]

if (asym \leq 0.1) then

****** April 2005****

Asymmetric effect in conc. gradient: asym*Ac*cos(4.0*(tnt+phiconc))

\[ :*(1.0+\text{Ac}\times\cos(2.0\times(tnt+\text{phiconc})) \]
\[ +\text{asym}\times\text{Ac}\times\cos(4.0\times(tnt+\text{phiconc})) \]
\[ /\text{ayy} \]

else

\[ \text{ayy} = 1.0 + \text{Ac}\times\text{Bc}\times\cos(2.0\times\text{phiconc}-2.0\times\text{phieddy})/2. \]

****** April 2005****

Asymmetric effect in conc. gradient: asym*Ac*cos(4.0*(tnt+phiconc))

cc4=crest

\[ *(1.0+\text{Bc}\times\cos(2.0\times(tnt+\text{phieddy})) \]
\[ +\text{asy}\times\cos(tnt+\text{phieddy})) \]
\[ *(1.0+\text{Ac}\times\cos(2.0\times(tnt+\text{phiconc})) \]
\[ +\text{asym}\times\text{Ac}\times\cos(4.0\times(tnt+\text{phiconc})) \]
\[ /\text{ayy} \]
end if

if (asym \leq 0.1) then

else

\[ \text{raa}=\text{eddy}\times(1.0+\text{Bc}\times\cos(2.0\times(tnt+\text{phieddy})) \]
\[ +\text{asy}\times\cos(tnt+\text{phieddy})) \]
Bedload transport

Description of wave-related bedload transport, according to Meyer-Peter and Müller (1948), Engelund and Fredsoe (1976) (both not in report) and the bedload formula by Ribberink (1998). Note that the Shields parameter is based on the second order Stokes free-stream velocity profile.

```fortran
1340c calculate wave induced bed load transport (so no current!):
1341c----
1342c Friction factor, ks=D50 is based on Ribberink 1998 for low
1343c shields numbers (shields < 1), maximum friction factor = 0.3:
1344   if((3.0*0.046/aa).lt.0.63) then
1345     FW=EXP(5.213*(3.0*0.046/aa)**0.194-5.977)
1346   else
1347     FW=0.3
1348   END IF
1349C Free stream velocity:
1350   VELY=U0*COS(TNT)+Usnd*COS(2.0*TNT)
1351C Shear stress calculation:
1352c SHY1=0.5*FW*rhof*ABS(VM(mp1,1)*u0)*(VM(mp1,1)*u0)/(gra*drho*DIA)
1353c SHY1=0.5*FW*rhof*ABS(VELY)*VELY/(gra*drho*DIA)
1354c
1355c-----
1356c bed load transport of Meyer-Peter Muller (1948)
1357   if(abs(shy1).lt.0.047) goto 761
1358   IF(SHY1.GE.0.0) THEN
1359     THETA3=8.0*(SHY1-0.047)**1.5
1360   END IF
```
THETA3=-8.0*(ABS(SHY1)-0.047)**1.5

if(abs(SHY1).lt.0.047) goto 961

THETA5=9.55*(sqrt(SHY1)-0.7*sqrt(0.047))*(SHY1-0.047)

THETA5=-9.55*(sqrt(ABS(SHY1))-0.7*sqrt(0.047))*(ABS(SHY1)-0.047)

if(abs(SHY1).lt.thetacr) goto 1061

THETA7=11.0*(SHY1-thetacr)**1.65

THETA7=-11.0*(ABS(SHY1)-thetacr)**1.65
Ripple predictor

Calculations of ripple dimensions according to Wiberg and Harris (1994) and Mogridge et al. (1994) (corrected with erratum of Mogridge et al. (1995)).
SUBROUTINE HYDRAULIC(RHEI,RLEN,Z0,CREST,
 : UX,UY,WS,ucc,period,d50,d,an,Usnd,VIS,
 : dstar,F25)

VIS=1.0E-2

read(55,*) Usnd

GOTO 1001

read(55,*) impose,rlen_imp,rhei_imp
IF(impose.eq.0) THEN
C
C *******************************************************************
C ****** IMPOSITION OF MAXIMUM STEEPNESS = 0.14 ***************
C ****** IMPOSITION OF MINIMUM STEEPNESS = 0.105 ***************
C *******************************************************************
C*******************************************************************
C*****Calculation of lengths and heights of wave-generated ripples**
C*******************************************************************
C PD = Wave period
C A0 = Semi-orbit length of water motion
C D50 = Sediment grain size
C doD = 2.*A0/D
C X2 = Rho*D/(Gamma_s * T**2)
C Rh = Ripple height
C Rl = Ripple length
C
C 1001 CONTINUE
C ****** IMPOSITION OF MAXIMUM STEEPNESS = 0.14 ***************
C Steepcheck=RHEI/RLEN
if(Steepcheck.GT.0.14)RHEI=0.14*RLEN

C ****** IMPOSITION OF MINIMUM STEEPNESS = 0.105 ***************
C Steepcheck=RHEI/RLEN
if(Steepcheck.LT.0.105)RHEI=0.105*RLEN

ELSE IF(impose.eq.1) THEN

chi=D50/(981.0*1.65*PD**2)
doD=ODIA/D50

RHEII = D50
RLENN = D50
drdvert = 8.542 - 10.822 * chi**0.03967
rdvert=10**drdvert
advert = (rdvert/0.134)**(1./0.95)
dadvert = ALOG10(advert)
dad=ALOG10(doD)

if(dad.gt.dadvert) then
    xxx=dad-dadvert
    yyy=0.00177059-3.739256 * xxx**1.7232273
    drd=yyy+drdvert
    rdd=10**drd
else
    xxx=dad-dadvert
    xxx=abs(xxx)
    yyy=0.00132254 + 2.641975 * xxx**1.886534
    drd=drdvert-yyy
    rdd=10**drd
end if
if(rdd.lt.1) rdd=1
RHEI=RDD*D50

Ripple length:
F1 = 1.07*chi**0.05
doD=10**(13.373-13.772*(chi**0.02054))
dstarol=dooD/F1
Theta = ATAN(F1)
rdoD=dooD/dstarol

a1oD=dstarol-2*dooD*tan(theta/2)*cos(theta)
a2oD=dstarol+2*dooD*tan(theta/2)

RLMAX = F2 * D50
R = 2. * F2 * D50
Aa = (F2*D50)/F1
A1 = Aa - (R * TAN(Theta/2)*COS(Theta))
A2 = Aa + R * TAN(Theta/2.)

IF(doD.LE.a1oD) RL = F1 * doD
IF(doD.GE.a2oD) RL = dooD
IF(doD.GT.a1oD.AND.doD.LE.a2oD) THEN
    ALPHAA = ACOS((a2oD-doD)/(2*dooD))
    RL = -dooD + 2*dooD*SIN(ALPHAA)
end if
RLEN=RL*D50

********************************************************************
IMPOSITION OF ACTUAL RIPPLE DIMENSIONS
write(28,'('''*** RIPPLE DIMENSIONS IMPOSED ***'''))
ELSE
3803c if(impose.eq.2) rlen=rlen_imp
3804c if(impose.eq.2) rhei=rhei_imp
3805 rlen=rlen_imp
3806 rhei=rhei_imp
3807c DeltaFlume Run A08a, ripple length and height (cm)
3808c RLEN=43.0
3809c RHEI=6.0
3810c **************************************************************
3811 end if
3812c END IF
3813c
3814 1001 CONTINUE
3815c ****** IMPOSITION OF MAXIMUM STEEPNESS = 0.14 **************
3816c Steepcheck=RHEI/RLEN
3817c if(Steepcheck.GT.0.14) RHEI=0.14*RLEN
3818c***************************************************************
3842 IF(impose.EQ.0)
3843 : WRITE(28,'(//'' RIPPLE PRED. METHOD BY WIBERG AND
3844 :HARRIS (1999)''))
3845 IF(impose.EQ.1)
3846 : WRITE(28,'(//'' RIPPLE PRED. METHOD BY MORGRIDGE (199$)''))
3847 IF(impose.EQ.2)
3848 : WRITE(28,'(//'' RIPPLE DIMENSIONS IMPOSED''))
3849c
3851 : WRITE(28,'('' BED TYPE IS PLANE''))
3853 : WRITE(28,'('' RIPPLE BED TYPE IS ORBITAL''))
3855 : WRITE(28,'('' RIPPLE BED TYPE IS SUB-ORBITAL''))
3857 : WRITE(28,'('' RIPPLE BED TYPE IS AN-ORBITAL''))

Reference concentration

3901 Tc=(PD*acos((-U0+(U0**2+8*(0.25*U0)**2)**(0.5)))/(4*(0.25*U0))))/(PI)
3903c
3904 Tt=PD-Tc
3905c
3906 Ucr=U0+Usnd
3907c
3908 Utr=U0-Usnd
chic = \frac{D_{50}}{(1.65 \times 981.0 \times (2 \times T_c)^2)}

chit = \frac{D_{50}}{(1.65 \times 981.0 \times (2 \times T_t)^2)}

dstar = D_{50} \times \left(\frac{(1.65 \times 981.0)}{\text{VIS}^2}\right)^{0.33333333333}

mobc = \frac{(Uc_r)^2}{(D_{50} \times 1.65 \times 981.0)}

mobt = \frac{(Utr)^2}{(D_{50} \times 1.65 \times 981.0)}

WRITE(*,'(Refcon method? (Nielsen=0; Werf=1; Impose (g/l)=2); )')
READ(5,*), Method

READ(55,*) Method, refcon

*******************************************************************
*****Reference concentration by Nielsen (1986): ********************
*******************************************************************
IF(Method.EQ.0) C0=0.0022*THR**3

*******************************************************************
*****Reference concentration by van der Werf & Ribberink (2005): **
*******************************************************************
IF(Method.EQ.1) C0=((23.82/(dstar**(1.25)))*(Tc/Pd*chic* (mobc**(1.75)))+Tt/Pd*chit*(mobt**(1.75)))

*******************************************************************
*****Imposition of reference concentration: ****************************
*******************************************************************
IF(Method.EQ.2) C0=refcon/2650

END IF

WRITE(28,'(REFERENCE CONCENTRATION BY NIELSEN 1986:')')
WRITE(28,'(REFERENCE CONCENTRATION BY VAN DER WERF 2005: ')')

WRITE(28,'(PARAMETERS VAN DER WERF (2005): ')')
WRITE(28,'(Ucrest= ',F6.3, cm/s')') Ucr
WRITE(28,'(Utrough= ',F6.3, cm/s')') Utr
WRITE(28,'(Tcrest= ',F6.3, s')') Tc
WRITE(28,'(Ttrough= ',F6.3, s')') Tt
WRITE(28,'('' Chi_crest= '',E10.4,'' (-)''')') chic
WRITE(28,'('' Chi_trough= '',E10.4,'' (-)''')') chit
WRITE(28,'('' Mobility crest= '',e10.4,'' (-)''')') mobc
WRITE(28,'('' Mobility through= '',E10.4,'' (-)''')') mobt
WRITE(28,'('' D*= '',F6.4,'' (-)''')') dstar
WRITE(28,'(/'' PARAMETERS MOGRIDGE (1994):'')')
WRITE(28,'('' doD= '',E10.4, '' '')') doD
WRITE(28,'('' chi= '',E10.4, '' '')') chi
WRITE(28,'('' lrdvert= '',E10.4, '' '')') drdvert
WRITE(28,'('' rdvert= '',E10.4, '' '')') rdvert
WRITE(28,'('' advert= '',E10.4, '' '')') advert
WRITE(28,'('' ladvert= '',E10.4, '' '')') dadvert
WRITE(28,'('' lad= '',E10.4, '' '')') dad
WRITE(28,'('' x1= '',E10.4, '' '')') xxx
WRITE(28,'('' y1= '',E10.4, '' '')') yyy
WRITE(28,'('' lrd= '',E10.4, '' '')') drd
WRITE(28,'('' rd= '',E10.4, '' '')') rdd
WRITE(28,'(/'' ripple height= '',F6.3, '' cm '')') RHEI
WRITE(28,'('' f1= '',E10.4, '' '')') f1
WRITE(28,'('' looD= '',E10.4, '' '')') dooD
WRITE(28,'('' dstarol= '',E10.4, '' '')') dstarol
WRITE(28,'('' theta= '',E10.4, '' '')') theta
WRITE(28,'('' rd= '',E10.4, '' '')') rd
WRITE(28,'('' a1oD= '',E10.4, '' '')') a1oD
WRITE(28,'('' a2oD=',E10.4, '''' )') a2oD
WRITE(28,'('' RL=',E10.4, '''' )') RL
WRITE(28,'(/'' shieldsx=',F7.3, '' cm'' )') bloadx