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This report on 1DV models has been prepared for the National Institute for Coastal and Marine Management Rijkswaterstaat (RIKZ) as part of the project Z2529 “Ontwikkelingen in de procesmodellering van de kustzone”. First, the presently available 1DV models are described focusing on the underlying physics and their merits and shortcomings as found in previously performed validation studies. Besides necessary future developments are identified and a sediment transport model is proposed including many of these features and with a structure which facilitates the inclusion of future developments by all NCK-partners.

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1 Introduction

1.1 General

This report on IDV models has been prepared for the National Institute for Coastal and Marine Management Rijkswaterstaat (RIKZ) as part of the project Z2529 “Ontwikkelingen in de procesmodellering van de kustzone”. On the one hand, the presently available IDV models are described focusing on the underlying physics and their merits and shortcomings as found in previously performed validation studies. On the other hand, necessary future developments are identified and a sediment transport model is proposed including many of these features and with a structure which facilitates the inclusion of future developments by all NCK-partners. The development of such a model has a long-term character and requires the support of all NCK-partners. This report can be seen as a first step and a basis for discussion; a follow-up involves the generation of financial support by RIKZ and WL/Delft Hydraulics and a further specification of the model set-up.

1.2 Relevance of IDV models

Depending on the dominant processes to be described, various sediment transport schematizations can be applied. For instance, in the cross-shore transport model UNIBEST-TC, a quasi-steady bed load formulation, assuming instantaneous response of the sediment to a time-varying near-bed orbital velocity, is used combined with a time-averaged approach for the suspended sediment flux over the height. Therewith, the phase-relationships between velocity and concentration are neglected. A more general sediment transport model, which covers all combinations of currents and waves, breaking and non-breaking, requires modelling of the intra-wave period oscillations of the velocity field, the field of suspended sediment and the bed load, including interaction with possible bed forms. IDV unsteady models resolving the time- and depth-dependency of the velocity and concentration fields are the simplest models in this intra-wave category by assuming that the horizontal variations in the hydrodynamics and sediment distribution are small compared to the vertical variations.

The development and refinement of IDV unsteady models provides us with further information about the complex processes of sediment suspension enabling a further improvement of engineering transport models. As such the IDV unsteady models not only increase our knowledge about the sediment transport processes but provide us with a way of improving transport descriptions in morphological models by: 1) parameterization of the unsteady IDV models, 2) by making an initial effort of tabulating the results of the intra-wave model for a specific situation, after which the morphodynamic model is run at relatively low costs, or 3) by finding analytical approximations to the governing equations.

The model proposed here should be considered as a “national sand transport model” acting as a ‘knowledge carrier’ (‘kennisdrager’). Besides, an important aspect of the here proposed
model as compared to presently available models is the extension to field situations by including e.g. irregular waves, wave-induced streaming and the treatment of the complete water column. In this way, a model can be obtained that can give us important information for the improvement of engineering tools.

1.3 Questionnaire

In the MAST-III SEDMOC programme in which University of Twente (UT), Delft University of Technology (DUT) and WL Delft Hydraulics (WL) are involved, one of the important objectives is the further development of 1DV transport models. In order to combine the efforts of the various NCK-partners in improving the 1DV models, WL has initiated discussions about co-operation on this topic aiming at the development of a "national sand transport model". Besides providing new developments itself, WL would have a co-ordinating role and integrate new developments from all partners in a numerical model available to all partners. WL has invited University of Utrecht (UU), University of Twente and Delft University of Technology to describe their ideas regarding organisational aspects and contents. The people involved are:

1. DUT: Jan van de Graaff, Paul Sistermans and Marjolein Dohmen-Janssen
2. UT: Jan Ribberink, Wael Hassan
3. UU: Leo van Rijn
4. WL: Judith Bosboom, Leo van Rijn, Roel Uittenbogaard, Gert Klopman (Albatros Flow Research)

The results of the inventory are used in Chapter 4 where the necessary future developments are described.

1.4 Outline of this report

In Chapter 2, an overview is given of the two available 1DV models which could serve as a starting point of the model extensions. The two models are: the NEREUS-C boundary layer model and the POINT-MUD model. The focus is on the differences between the two models. One of the two, the NEREUS-C model has been extensively used in validation studies on sand transport (using oscillating water tunnel data). An overview of these validation studies is given in Chapter 3. Based on Chapter 2 and 3 and on the results of the questionnaire, the preferred future developments are described in Chapter 4. Chapter 5 proposes a set of model equations and discusses the model structure and organisational framework.

1.5 Acknowledgements

This work was co-sponsored by the SEDMOC project, in the framework of the EU-sponsored Marine Science and Technology Programme (MAST-III), under contract no. MAS3-CT97-011S. Further, the input of all partners in the Netherlands Centre for Coastal Research (NCK) is acknowledged.
2 IDV models NEREUS-C and POINT-MUD

At present, two models are available at WL which could serve as a starting point for the new model developments, i.e. the NEREUS-C wave boundary layer model (Klopman/Ribberink, see Ribberink et al., 1995) and a directional point model (POINT-MUD; Winterwerp and Uittenbogaard, 1997). The development of the latter was funded jointly by WL/Delft Hydraulics and Rijkswaterstaat RIKZ.

The list below gives a first idea about the differences between the two models:

<table>
<thead>
<tr>
<th>NEREUS-C</th>
<th>POINT-MUD</th>
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<tr>
<td>1 horizontal velocity component</td>
<td>2 horizontal velocity components</td>
</tr>
<tr>
<td>intra-wave, regular waves</td>
<td>short wave-averaged</td>
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<tr>
<td>hydrodynamics and sediment concentration</td>
<td>hydrodynamics and sediment concentration</td>
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<tr>
<td>uncoupled</td>
<td>coupled</td>
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<tr>
<td>turbulence closure using Prandtl mixing</td>
<td>turbulence closure ( k - \varepsilon ) model</td>
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<tr>
<td>length</td>
<td>including stratification</td>
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<tr>
<td>boundary layer approximation</td>
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<td>density effects in momentum equation in</td>
<td>term</td>
</tr>
<tr>
<td>development (UT)</td>
<td>no density effects other than turbulence</td>
</tr>
<tr>
<td>sand transport, one fraction</td>
<td>damping in momentum equation focus on mud,</td>
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<td>several fractions</td>
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In order to illustrate the different schematisations made in the respective models, this section starts with the general governing equations (without the Coriolis term). Further, the assumptions made in the various models are indicated. For simplicity, we consider only a 2DV situation and a constant density (not affected by sediment concentration), such that the water motion is fully described by the 2D Navier Stokes mass and momentum equations, in which the horizontal velocity \( u \), the vertical velocity \( w \) and the pressure \( p \) occur as dependent variables. Phase-averaging of the Navier Stokes equations, so that the fluctuations on the turbulence time-scale are averaged out, results in the Reynolds-averaged mass and horizontal momentum equation:

\[
\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0; \tag{2.1}
\]

\[
\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uw}{\partial z} = \frac{1}{\rho} \left( \frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial z} \right), \tag{2.2}
\]

in which \( \tau_{xx} \) is defined via the Boussinesq hypothesis:

\[
\tau_{xx} = \rho (\nu + \nu) \frac{\partial u}{\partial z}, \tag{2.3}
\]
with \( V \) is the molecular viscosity and \( V_i \) is the eddy viscosity or turbulent eddy diffusivity of fluid momentum, which must be determined from a turbulence closure model.

In principle the momentum equation can be applied to a single sediment particle in a turbulent flow. For particles much smaller than the turbulence length scale, the particles can perfectly follow the flow and we are dealing with a single-phase flow. In that case the momentum equation simply states that the sediment velocity is equal to the water velocity, except in vertical direction where it is equal to the fluid velocity minus the particle fall velocity.

Conservation of mass is then applied to the sediment making the assumption of upward transport due to turbulence diffusion as for the fluid with a diffusivity \( \varepsilon = \beta V \). This yields after Reynolds averaging:

\[
\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial}{\partial z} \left[ (w - w_i) c \right] = \frac{\partial}{\partial z} \left[ \beta (v + v_i) \frac{\partial c}{\partial z} \right],
\]

(2.4)

in which \( c \) denotes the turbulence averaged concentration and \( w_i \) the particle fall velocity. This equation must be solved subject to the boundary conditions of zero flux at the water surface and a specified concentration close to the bed.

Both NEREUS-C and POINT-MUD neglect the non-linear convective terms assuming that the velocity magnitude is small compared to the wave phase speed. This gives:

\[
\frac{\partial u}{\partial t} = -\frac{1}{\rho} \left( \frac{\partial p}{\partial x} + \frac{\partial \tau}{\partial z} \right),
\]

(2.5)

and

\[
\frac{\partial c}{\partial t} = \frac{\partial}{\partial z} \left[ w_i c \right] + \frac{\partial}{\partial z} \left[ \beta (v + v_i) \frac{\partial c}{\partial z} \right],
\]

(2.6)

Herewith the term \( \partial nw/\partial z \), responsible for the wave-induced streaming is neglected. Besides the turbulence closure, the main difference between NEREUS-C and POINT-MUD is the way in which the pressure gradient is prescribed.

**NEREUS-C**

In NEREUS-C, the boundary layer approximation is made of a depth-invariant pressure equal to its value just outside the boundary layer where the Reynolds shear stresses approach a constant mean value. Therewith, the mean pressure gradient is zero and:

\[
\frac{\partial u_m}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x}.
\]

(2.7)
where $u_\infty$ is the prescribed free stream velocity outside the wave boundary layer. This wave boundary layer equation is then solved to the no-slip boundary condition at the bed and the boundary condition of the wave velocity approaching the quasi-constant $(\partial / \partial z = 0)$ oscillatory velocity at the edge of the wave boundary layer.

**POINT-MUD**

In POINT-MUD the pressure gradient is driven by the slope of the mean water surface, which is either prescribed by the user or computed every time-step from the user-prescribed depth-averaged velocity. A wind-forcing can be included. Applications of the model focus on temperature stratification and mud transport.
3 Overview of NEREUS-C validation studies

3.1 Introduction

In this chapter a literature review of the validation of the one-dimensional vertical (IDV) intra-wave transport model (NEREUS-C) is given. This model is based on the momentum equation for water, using the Prandtl mixing-length concept as turbulence closure, and an advection-diffusion equation for sediment. The numerical flow model was built by Klopmann (1990), the numerical sediment model was developed by Ribberink and Al Salem (1991) based on the SUSTIM model developed by Meyer and Van Rijn. Three different studies which discuss this model were found: Ph.D. thesis of Al Salem (1993), with the corresponding paper of Ribberink et al (1995), MSc. thesis of Hassan (1996) with corresponding paper of Janssen et al (1997) and a paper in which four models are compared, Davies et al (1997). Note that validation studies of POINT-MUD are not described here since this model has not been applied to compute intra-wave transport of sand.

3.2 Al Salem et al.

Al Salem (1993) carried out a sensitivity analysis in order to learn the tendencies of the model with respect to variations in input conditions and model parameters. This analysis shows that the model results confirm the measured period influence on the net transport rate. Furthermore, the model results are influenced by the formulation for the reference concentration.

The model was verified with experimental results that were obtained from series B and C experiments in the Large Oscillating Water Tunnel (LOWT) of WL/Delft Hydraulics. These experiments involve irregular and regular asymmetric waves (series B and C) and regular sinusoidal waves (series C) without a current and were performed by Al-Salem in 1993. The sand bed consisted of sediment with $D_{50}=0.21$mm. Because the model is not equipped with input facilities for irregular waves, only the regular wave experiments are used.

The boundary-layer flow model showed a reasonable agreement with the measured instantaneous velocities in the upper part of the boundary layer. The net flow velocity profile is not modelled perfectly, however the right tendency is predicted by the model. The sediment concentration model is not able to predict the instantaneous sediment concentrations at higher elevations. The model overestimates the concentrations and the computed phase-lag is much smaller than the measured one. The smaller measured concentrations may be explained by mobile bed effects that lead to turbulence damping, that is not involved in the model. The larger phase lag of the measurements could be caused by vertical sorting effects, that are not taken into account in the model. Another cause of the larger phase lag in the measurements is the existence of second peaks that are generated at flow reversal and become important at higher elevations. It should be mentioned that the model is not able to reproduce these flow reversal peaks.
The model is able to predict the correct $u_{ms}$-influence on the time-averaged concentrations, but the quantitative agreement is not always satisfactory with the experimental results. The net sediment flux of the asymmetric-wave experiment is predicted rather well, however, the measured offshore directed sediment flux occurs at a lower elevation than computed. The calculated total net transport rates are larger, but less than a factor 2, than the measured ones. The increase in net transport rate for increasing $u_{ms}$ calculated with the model is smaller than the increase that was found from the measurements.

Al Salem concluded that a real improvement of the model could only be expected by modelling additional detailed processes such as the pick-up mechanism during flow reversal, vertical sorting of sediment and turbulence damping. The model is calibrated in order to create a possible practical model which is able to predict the parameters of the above mentioned experiments.

### 3.3 Hassan and Janssen et al.

Hassan (1996) and Janssen et al (1997) verified the model with data for two different grain sizes. The verification of the model is performed with data from LOWT containing a regular sinusoidal wave with current for sediment with $D_{50}=0.21$mm (series E, Katopodi, et al, 1994) and $D_{50}=0.13$mm (series H, Janssen et al, 1996). The model was not able to simulate the measured time-averaged velocities and concentrations; they were both overestimated. This may be caused by sediment-flow interaction, which is a very important phenomenon in the sheet-flow layer, but is not included in the model. The sheet-flow layer acts as an increased roughness, which would cause a decrease in velocity gradient close to the bed and an increased velocity gradient further away. The sheet flow layer may also cause turbulence damping, which would reduce the concentration.

The quantity and the tendency of the calculated sediment fluxes do not agree with the measurements. This is caused by the smaller phase lag between velocity and concentration as calculated by the model than the measured phase lag. The computed total net transport rates are overestimated, however for $D_{50}=0.21$mm this is less than a factor 2.

The model was calibrated in order to find better agreement with the measurements. The main shortcoming of the model is the overprediction of the sediment concentrations that may be caused by two reasons: an incorrect modelling of the sediment concentration at the bed and an incorrect modelling of the sediment mixing which determines the shape of the sediment concentration profile.

The model was modified in such a way that the turbulent eddy viscosity could be described in three different ways: using the original Prandtl mixing length, using the mixing length distribution of Armanini and Ruol (1988) and reducing the eddy viscosity, as calculated from the original Prandtl mixing length, with a certain factor over the whole depth. A sensitivity analysis was carried out to study the effects of the input parameters on the model. The best results were obtained by reducing the eddy viscosity, that was calculated by the Prandtl mixing length model and using the sheet-flow layer thickness as roughness height. The parameters that are used for this optimization are realistic physical values and
give best fitting for time-averaged velocities and concentrations for both grain sizes. However, in the sheet flow layer still discrepancy exists between the calculations and the measurements. This is caused by the importance of grain-grain and grain-fluid interactions in the sheet flow layer, which are not included in the model.

It was recommended to verify the model with other experiments with different flow conditions and grain-sizes. The 1DV model can be improved by a better simulation inside the sheet-flow layer by including the density change and the hindered settling effect. The flow can be considered as a suspension layer flow and a sheet-flow layer flow. Furthermore it is recommended to take into account the interaction between the sediment and the flow as well as the vertical sorting of the sediment.

3.4 Davies et al.

The 1DV model NEREUS-C has been compared with three other transport models as part of the MAST2 project (Davies et al, 1997). None of the models is able to predict the time-dependent concentration rather well. This is mainly due to the inability of conventional turbulence diffusion schemes to represent the entrainment of sediments at flow reversal. The comparison was performed with data from LOWT. The above mentioned series B (Al Salem, 1993) was used to assess the performance of the various models in predicting net sediment transport rates. Series C (Al Salem, 1993) and series E (Katopodis et al, 1994) experiments were used to compare the models in case of an asymmetrical wave and a sinusoidal wave with and without a current. The sand bed composition was the same for all conditions, D_{50}=0.21mm. The above mentioned 1DV model NEREUS-C is called the ‘mixing length’ model, because a mixing length approach is used to derive a (time-dependent) eddy viscosity.

The ‘STP’ model, developed by Danish Hydraulics Institute, also uses an eddy viscosity approach to model the vertical distribution of sediment. This model is also one of the four models that was tested. The other two models that were tested are the one-equation, turbulent kinetic energy, closure model, ‘t.k.e.’ model, developed by Davies (1995) and the ‘k-L’ model of Huynh Thanh et al. (1994). These are two typical numerical turbulence-closure models that have been used to study sediment transport. In the mixing length and k-L model only the suspended load is calculated. In the two remaining models, the sediment transport rate includes bedload computed by applying a quasi-steady bed load formula below the reference level. The damping process is represented in a complicated way in the k-L model and has a very small effect on the t.k.e model, but is not taken into account in the mixing length and in the STP model.

The comparison between the four models is performed with the uncalibrated versions of the models. The emphasis of the comparisons of the models lies on the net sediment fluxes and also on the more detailed behaviour of the models, e.g. time variation in sediment concentration. First, a comparison is performed for sinusoidal waves without a current. The mixing length model overpredicts the time-averaged concentration at all heights. This is due to a relatively large sediment diffusion coefficient, especially at higher levels. The mismatch of the models to predict the phase angle of the time-dependent concentration is
due to flow reversal peaks. None of the models include a detailed description of the boundary layer physics to represent this convection peaks.

For the asymmetrical waves, the time averaged concentration and the flux are studied only. The mixing length model is again overpredicting the time-averaged concentration more than the other models. The fluxes are modelled quite well, but the height of the zero flux is overestimated by all models, the largest overprediction is given by the mixing length model. The prediction of the four models for the net sediment transport rates would be considered as extremely good in coastal engineering practice. It should be noted that all of the experiments that were used to compare the models, were performed with sand with $D_{50}=0.21\text{mm}$, for which the transport rate was dominated by transport in the sheet flow and lower suspension layers. For finer sediment, the situation may be different.

The final comparison was made for sinusoidal waves with a current, series E. The time-averaged concentration is again overpredicted by the mixing length model. None of the models is able to predict the concentration peaks as a result of the flow reversal peaks. The predicted values of the flux in the sheet flow layer are too small for all models. However, in general the fluxes are overestimated, due to the overprediction of the concentration in the suspension layer. The measurements show a flux in the current direction in the lower suspension layer, but at heights above about 3 cm, the transport is in opposite direction. The height of the change in direction of the flux is overestimated by the models, especially by the mixing length model.

Davies suggests new experimental research to determine in the first place the velocity field in the sheet flow layer to accompany the existing knowledge of concentration. By use of two-phase flow models it should be possible to obtain a continuous description of grain-grain and fluid-grain interactions.

### 3.5 Conclusions and recommendations

From the three above mentioned studies it can be concluded that the 1DV NEREUS-C model:

- overpredicts time averaged concentrations. This may be explained by the presence of turbulence damping and sediment flow interaction that is not taken into account in the model.
- shows a smaller phase lag than the measured one. This may be caused by vertical sorting effects and the existence of secondary peaks near flow reversal, that are both not included in the model.

The different researchers recommended to:

- take more detailed processes, such as pick up mechanisms during flow reversal, vertical sorting of sediment and turbulence damping into account.
- verify the models with other experiments with different grain sizes and wave conditions.
- do some experiments to measure the velocity field in the sheet flow layer in order to accompany the existing knowledge of the concentrations. These experiments must give more insight in the grain-grain and grain-fluid interaction in the sheet flow layer.
4 Processes to be included in IDV sand transport model

4.1 General

In this chapter, an overview is given of the ideas considering an improved IDV sand transport model. One can roughly distinguish between two categories. In the first category falls the inclusion of additional physical processes, which are conceptually developed thoroughly enough to directly implement in the model. This will extend the applicability of the model and provide a way of further studying those processes, their effect on the sediment transport and the modelling concepts. The second category involves physical processes for which the model concepts are still less developed. The model structure should be flexible enough such that at a later stage those topics can easily be included.

4.2 Turbulence modelling

Turbulence closure

From Chapter 3, it is clear that the mixing-length approach (with linearly increasing mixing length away from the bed) to derive a time-dependent eddy viscosity severely overestimates the viscosity. Although the flow is described with reasonable accuracy, the sediment concentrations are severely overestimated as a result of overestimation of the diffusivity at higher elevations in the wave-boundary layer. Results from Davies et al. (1997) suggest that the use of more sophisticated turbulence models eliminates this problem. Marjolein Dohmen-Janssen adjusted the mixing length approach in two different ways: 1) by introducing a height-independent reduction factor $\beta$ for the viscosity; and 2) by allowing the mixing length to become constant at a certain distance away from the bed. The use of a one-equation turbulence model however, in which a transport equation for the turbulent kinetic energy $k$ is included in the flow description, allows a more accurate description of the vertical distribution of turbulence. The length scale of the turbulence must be prescribed. In a two-equation model the latter disadvantage is removed by adding an additional equation, for instance the a transport equation for the dissipation $\varepsilon$.

Turbulence damping due to stratification

An additional advantage of a one- or two-equation model is that the effect of density gradients in the high concentration sheet flow layer on the turbulence level are automatically taken into account; both the $k$-equation and $\varepsilon$-equation include a damping term which depends on the density gradient. The only way to include this in a mixing length model is to adjust the viscosity and diffusivity on the basis of the Richardson number. The $k-\varepsilon$ model which is part of the POINT-MUD model has undergone a extensive
amount of research and testing and the model concept could be implemented in the new model under consideration.

4.3 Sediment

Graded sediments

The inclusion of graded sediments requires the division of the sediment mixture in various grain-diameter fractions and the application of the advection-diffusion equation per fraction. The bed boundary condition for the sediment needs to be adjusted for a fractional approach, inclusive of possible hiding-and exposure or armouring corrections. This subject is part of research activities (experimental and numerical) of DUT, UT and WL/Delft Hydraulics in the framework of SEDMOC.

Sediment-flow interaction

The flow in the high-concentration sheet flow layer is affected by the higher density. This can be taken into account by solving the momentum equation for a sediment-water mixture and the advection-diffusion equation as a set of equations which are physically coupled through the influence of the concentration on the density. This boils down to a momentum equation in which $pu$ appears rather than $u$. Another option is to apply the momentum equation for constant density, but model the shear stress as composed of a fluid-related and grain-related part in which the latter depends on the density according to Bagnold (1956). This topic is part of ongoing research at DUT as part of the PhD-work of Dohmen-Janssen and at UT in the framework of NICOP.

Detailed sheet flow modelling

Besides the coupling of momentum and sediment distribution equations as mentioned under sediment-flow interaction above, more advanced methods are possible to account for the sheet-flow phenomena, such as taking grain-grain interactions and interaction forces between grains and fluid into account. Also the time-varying bed level could be accounted for. This will in the near future be studied at UT in the framework of NICOP and will at this stage not be taken into consideration in the proposed 1DV model. The proposed model must be flexible enough to implement this approach at a later stage.

Sediment distribution model

The advection-diffusion equation assumes that the mechanism for upward transport of sediment is by turbulence diffusion, whereas in general also convection is important for the upward transport. A different sediment distribution model based on convection or combined convection-diffusion could be considered (Nielsen, 1992). The convection becomes important not only for rippled bed cases but also in the description of graded sediment, since the importance of convection varies for different sediment fractions; diffusive characteristics are displayed by finer sediment fractions while the coarse fractions are more influenced by the convective mechanisms. This topic has so far not been taken up in the
Netherlands and might be a topic which could fit in the PhD-programme of Paul Sistermans at DUT.

**Plane versus rippled beds**

In case of bedforms, ripples or dunes, the near-bed current field contains organized vortices and the sediment flux is not necessarily related to the concentration gradient as assumed in a pure diffusive description; besides diffusion processes, convection processes have to be taken into account in an exact description. Although in principle a complex 2DV process for which models are still under development, a convection based 1DV model could be used as a first step (Nielsen, 1989). An empirical ripple estimator could then determine whether diffusion or convection mechanism should be dominant. In view of the still limited knowledge on sediment transport above a rippled bed and the fact that the plane bed situation is probably dominant in field situations, at present no attempts will be made to include this.

**Sediment bed boundary condition**

It must be possible to choose several formulations formulated both as a reference concentration-type condition and as a pick-up type condition. At present in NEREUS-C the following formulations are included: the semi-theoretical formulation according to Engelund and Fredsoe (1976) and the empirical formulations according to Al-Salem (1993) and Zyserman and Fredsoe (1994), respectively. The latter has the advantage of an upper cut-off for the sediment pick-up rate at large values of the bed shear stress. Formulation of these boundary conditions in terms of a pick-up boundary condition can become important in case of higher velocities, fine sediment and small wave periods. Also the reference concentration of Van Rijn, which is applied a level higher than the previously mentioned ones will be included. In this latter case, the sand transport below the reference level will be modelled as bed-load transport (formula-type approach).

**Hindered settling**

The dependency of the fall velocity on the sediment concentration in a high-concentration flow will be taken into account using the conventional relationships for the fall velocity and the corrections for high concentrations. At present no hindered settling effects are taken into account in NEREUS-C.

### 4.4 Extension to field situations

To bridge the gap between the transport formula used in practical situations and the unsteady 1DV models which are not often applied outside a idealised (laboratory) situation, the extension to the complete water column, irregular waves and two horizontal velocity components as well as the inclusion of vertical velocities (and the resulting wave-induced streaming) is essential. These extensions are subject of research at WL, partly within the framework of SEDMOC.
Such an extended 1DV model could locally be applied to compute sediment concentrations and transport rates. The model input could either be known from measurements or from numerical field models. The latter means that the model structure must be such that implementation in other WL/RIKZ software such as Unibest-TC or Delft3D is possible. An implementation in field models does not necessarily mean that this is the road to follow in morphodynamic model applications. The direct use of such a detailed intra-wave transport model in a morphodynamic model is time-consuming from a computational point of view. The model however could serve as a reference to test simpler formulations against. Besides, the model could be used to improve presently available transport descriptions in morphological models by parameterization of the unsteady 1DV model. Note that the Danish STP model is at present the only intra-wave model to be applied in morphodynamic simulations; by making an initial effort of tabulating the results of the intra-wave model for a specific situation the morphodynamic model is run at relatively low costs.

**Complete water column**

Most 1DV models are based on a boundary layer approximation and therewith only capable of describing the processes near the sea bed. Experiments in the oscillating water tunnel which are generally used for model validation simulate exactly this situation of a purely horizontal flow with sediment transport concentrated close to the bed. In such a 1DV boundary layer model, the time-varying pressure gradient is prescribed above the wave boundary layer, which then under assumption of vanishing shear stresses outside the wave boundary layer reduces to imposing the derivative in time of the time-varying velocity outside the wave boundary layer. Further, the mean pressure gradient is assumed to be zero such that the mean shear stress is independent of the height. In (flume and) field situations, the sediment is not confined to the wave boundary layer and the assumption of a time-mean pressure gradient is not appropriate. Thus, an alternative model must be formulated. In order to be able to describe the complete water column, an alternative formulation must be used for both the mean and oscillatory pressure gradient. The mean pressure gradient is dominated by the slope of the mean water surface and can be assumed to be hydrostatic. The other contributions to the mean shear stress, i.e. as a result of the pressure and momentum fluxes due to the decaying wave motion and in breaking waves due to the change of momentum in surface rollers, can be assumed to be depth-invariant and are introduced by a wave-induced shear stress at the water level. Note that also a wind-stress at the water level can be applied. The oscillatory pressure gradient is, for shorter waves, a function of $z$. Above the boundary layer, a $\cosh(k_w(z+h))$ relation can be used, with the wave number $k_w$ determined from linear wave theory for the wave period in case of regular waves, or for the peak or mean period in case of irregular waves. At a later stage, this could possibly be refined by applying a different vertical structure, based on linear theory, for every frequency component.

**Irregular waves**

In principle, an arbitrary time-series of wave height or oscillatory velocity can be applied, which are for instance known from measurements. As such irregular waves are not a topic. However, the most likely model input in practical situations is a significant wave height and peak period. From these quantities, a representative velocity time-series could be
constructed having the same characteristics of asymmetry, long waves and amplitude modulation as a random wave field using the method which in now applied in Unibest-TC. When in addition the wave spectrum is known, more sophisticated irregular wave simulation software can be used to generate a time-series of irregular waves. For the computation of the vertical structure of the wave velocity, one is referred to the above section “complete water column”

**Wave breaking**

To introduce the effect of wave breaking, a wave-induced shear stress can be applied at the water surface. In a time-averaged sense this is easily performed by relating the shear stress introduced by the surface roller to the dissipation of roller energy as computed from a time-averaged wave propagation model. In this way, the undertow profile could be simulated. However, the solution in an intra-wave sense is less straightforward. When neglecting variations on the short-wave scale, a surfbeat-type model might provide the dissipation on the scale of the wave group. In addition, the increase of turbulence by wave breaking must be taken into account. Again, a choice has to be made considering the time scales for averaging. The intra-wave time-variation of the turbulence production due to wave breaking could be modelled according to Deigaard (1986). For now, we will restrict ourselves to the simulating an undertow profile by application of a time-averaged surface shear stress and increase of turbulence level.

**Waves and current under an angle**

This requires that a second horizontal velocity component be taken into account.

**Streaming**

In order to take vertical velocities and resulting wave-induced streaming into account we have to retain the non-linear convective terms in Equations (2.2) and (2.4). In order to still have a essentially 1DV system, the convective terms can be rewritten assuming that the waves propagate with a celerity $C_w = \left(C_{w,x}, C_{w,y}\right)$. In that case the $x$- and $y$-derivatives can be converted into time-derivatives using the relationship:

$$
\frac{\partial}{\partial x} = -\frac{1}{C_{w,x}} \frac{\partial}{\partial t},
\frac{\partial}{\partial y} = -\frac{1}{C_{w,y}} \frac{\partial}{\partial t}
$$

(4.1)

The celerity $C_w$ is in regular waves equal to the wave celerity and in irregular waves for instance the celerity corresponding to the peak or mean period. In a later stage, an extension is possible to a time-dependent celerity in irregular waves. The vertical velocity component can be obtained from the continuity equation.


5 Proposal for POINT-SAND model

5.1 Physical processes to be included

From the above chapters, a list of extensions (compared to NEREUS-C) follows for a first version of the new POINT-SAND model:

<table>
<thead>
<tr>
<th>POINT-SAND model</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 horizontal velocity components (and 1 vertical)</td>
</tr>
<tr>
<td>vertical velocities and wave-induced streaming</td>
</tr>
<tr>
<td>irregular waves with vertical structure based on integral spectral parameters</td>
</tr>
<tr>
<td>hydrodynamics and sediment concentration coupled</td>
</tr>
<tr>
<td>turbulence closure using Prandtl mixing length, but also $k - \varepsilon$ model including stratification and possibly $k$ model (including stratification)</td>
</tr>
<tr>
<td>complete water column via boundary conditions at water surface and depth-dependent pressure gradient</td>
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<tr>
<td>hindered settling</td>
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<td>sediment fractions</td>
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<tr>
<td>undertow computation</td>
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<tr>
<td>density effects in momentum equation</td>
</tr>
<tr>
<td>inclusion of bed load formula</td>
</tr>
<tr>
<td>reference concentration at grain level or at top sheet flow layer</td>
</tr>
<tr>
<td>Coriolis term</td>
</tr>
</tbody>
</table>

This can be realised using the following set of equations as a basis:

- The horizontal momentum equations read:

  \[
  \frac{\partial}{\partial t}\left( u - \frac{u^2}{C_{w,x}} - \frac{u v}{C_{w,y}} \right) + \frac{\partial}{\partial z} (uw) = \nu + \frac{1}{\rho} \left( -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} \right), \tag{5.1}
  \]

  \[
  \frac{\partial}{\partial t}\left( v - \frac{u v}{C_{w,x}} - \frac{v^2}{C_{w,y}} \right) + \frac{\partial}{\partial z} (vw) = -\gamma u + \frac{1}{\rho} \left( -\frac{\partial p}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} \right). \tag{5.2}
  \]

  where $\gamma$ is the Coriolis parameter

- The shear stress components $\tau_{xz}$ and $\tau_{zy}$ are determined using a turbulence closure model, via the Boussinesq-hypothesis:

  \[
  \tau_{xz} = (\nu + \nu) \frac{\partial u}{\partial z}, \tag{5.3}
  \]
\[ \tau_{zy} = (v_t + v) \frac{\partial v}{\partial z}. \] (5.4)

- The other shear stress components \( \tau_{xx}, \tau_{yy}, \) and \( \tau_{xy} \) are neglected. The turbulence viscosity \( v_t \) follows from a turbulence model \( (k-\varepsilon) \) model, Prandtl mixing length model.

- The vertical velocity component is determined from the continuity equation.

\[ \frac{\partial w}{\partial z} = \frac{1}{C_{w,x}} \frac{\partial u}{\partial t} + \frac{1}{C_{w,y}} \frac{\partial v}{\partial t}. \] (5.5)

- The sediment distribution equation (which will be formulated for several fractions) is determined from:

\[ \frac{\partial}{\partial t} \left[ c \left( \frac{uc}{C_{w,x}} - \frac{vc}{C_{w,y}} \right) + \frac{\partial}{\partial z} \left( (w-w_s)c \right) \right] = \frac{\partial}{\partial z} \left[ \beta (v_t + v) \frac{\partial c}{\partial z} \right]. \] (5.6)

Note that the formulations are at present formulated for constant density. The possibility to solve the momentum equations for varying density (dependent on the sediment concentration) without drastically changing the model structure is at present under consideration. The inclusion of the varying density is considered to take place in a later stage.

- The pressure gradients are determined according to Section 4.4.

### 5.2 Organisational structure

All NCK-partners supply new research results. The co-ordination is hands of WL; this involves the set-up of the model as mentioned under 5.1, the integration of newly available knowledge in the model and the version management. The model is available to all NCK-partners (open research versions). It must be realised that the joint development of the new model has a long-term character and requires the support of all NCK-partners. This report can be seen as a first step and a basis for discussion; a follow-up involves the generation of financial support by RIKZ and WL)Delft Hydraulics and a further specification of the model structure. The next paragraphs give some first remarks on the requirements in terms of model structure.

### 5.3 Model structure

**Flexibility**
In view of future extensions and the joint use of the model within the framework of NCK, a flexible, robust model is required which is easily extended and with contains various possibilities for the model input. Boundary conditions as well as integral conditions can be used such as a prescribed depth-averaged velocity. The computer language will be Fortran. The possibility of coupling with various WL/RIKZ models is another requirement. It is important that the model can easily reduce to less complicated situations; an example is the possibility of neglecting the vertical velocities such that the wave tunnel situation is recovered.

**Input and output**

The input and output parameters or time-series must be specified.

**Starting point**

At the moment, the possibility to use the POINT-MUD model as a starting point is investigated. The alternative is the set-up of a completely new model. At a later stage, the model scheme and the phases in the development (including verification and validation) will be further specified.
References


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