Modeling tidal sand wave recovery after dredging: effect of different types of dredging strategies

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1. Introduction

Tidal sand waves are rhythmic bed forms that are observed in various sandy tide-dominated shelf seas, such as the North Sea (Damen et al., 2018). They have wavelengths of hundreds of meters, heights of several meters and can typically migrate with several meters per year (Terwindt, 1971), in some cases much faster (Harris, 1989).

The presence of sand waves may pose a hazard to shipping lanes, as ships need a minimum water depth to safely navigate. Various approach channels to harbours, such as the Euro Channel to Rotterdam (Fig. 1), are located in a sand wave field (e.g., Levin et al., 1992; Dorst et al., 2011). Here the sand wave crests form the highest points in the seabed topography, which may pose a threat to the least navigable depth guaranteed in shipping lanes (Katoh et al., 1998). Shipping lanes are therefore frequently surveyed and dredged, because deposition of sediment and the recovery of sand waves in the channels after dredging reduce the navigable depth. Fig. 2 shows an example of the bed topography before and after dredging and the subsequent sand wave recovery.

Dredging of sand waves has two effects: the height of sand waves decreases, and the local mean bed level profile decreases if sand is extracted from the system (Knaapen and Hulscher, 2002). In an empirical model, Knaapen and Hulscher (2002) described sand wave regeneration using a Landau equation,

$$\frac{dA}{dt} = c_0 A - c_1 A^3.$$  \hspace{1cm} (1)

Here $A$ is the sand wave amplitude, which is a function of time $t$. Moreover, $c_0$ and $c_1$ are coefficients obtained by fitting with field data. The assumption of sinusoidal shapes implies that sand wave amplitude is half the sand wave height. However, dredging not only reduces sand wave amplitude/height, it also changes the shape of sand waves, and hence their evolution, which is not included in these type of models. This shortcoming calls for generic process-based knowledge on the response of sand waves to dredging that takes sand wave characteristics as shape effects into account. Up till now, such process-based studies are lacking.

The goal of this study is to gain insight in both the spatial and temporal aspects of dredging strategies in sand wave fields. The research questions of our work are as follows.

RQ1 What is the effect of a single dredging intervention at a sand wave crest, for a range of volumes, with or without dumping the dredged material in the trough?
RQ2 What is the effect of imposing a dredging criterion, which leads to repeated dredging interventions? In particular, what are the differences between dredging small amounts frequently, and dredging large amounts less frequently?

Answering these questions implies a first step towards optimizing dredging strategies.

To this end, we apply the idealized nonlinear process-based sand wave model developed by Campmans et al. (2018) to various dredging strategies as well as the adaptive temporal recurrence of dredging events. This model describes sand wave evolution in a horizontally periodic domain, which enables us to investigate the evolution of sand waves to equilibrium profiles within reasonable computational time, without complications due to inflow and outflow conditions (Krabben-dam et al., 2019). Other model studies of sand wave dynamics are at the moment less favourable as they require either too long computational time or have still difficulties to reach equilibrium states (e.g., Van Ger-wen et al., 2018).

An important property of tidal sand waves is their pattern dynamics, which occurs also on other spatial and temporal scales for other morphological bed forms. Dredging interventions can be seen as a local perturbation. In a flat bed this may trigger the instabilities associated with the formation of tidal sand waves (Roos et al., 2005) and tidal sand banks (Roos and Hulscher, 2006). In a finite amplitude setting, such a perturbation may trigger recovery mechanisms, as has been shown for shoreface-connected ridges (De Swart and Calvete, 2003) and tidal sand banks (Roos and Hulscher, 2006). This paper is structured as follows. Section 2 presents the model setup and introduces the different types of dredging strategies. In Section 3, the modeled sand wave response to dredging are shown. Finally, Sections 4 and 5 contain the discussion and conclusions, respectively.

2. Methods

2.1. Outline of process-based sand wave model

As pointed out in the introduction, in our study we use the nonlinear sand wave model developed by Campmans et al. (2018). This is an idealized model to investigate the finite amplitude dynamics of sand waves. Hydrodynamics and sediment transport are included in a schematized way. It solves the 2DV shallow-water equations. Turbulence is parameterized by a uniform vertical eddy viscosity and a partial slip boundary condition at the seabed (Hulscher, 1996). Sediment transport...
is modeled by a bed load formula that includes transport induced by the bed shear stress due to currents and waves, plus a correction accounting for the bed slope. The seabed evolution follows from the Exner equation, expressing sediment conservation. The model forcing includes wind-driven currents, wind waves and an M2 tidal current. The model domain is horizontally periodic. A detailed model description can be found in Appendix A.

2.2. Definitions of nautical and dredging parameters

In our model study the guaranteed channel depth is denoted by $D_{\text{min}}$ and the design dredging depth by $D_{\text{dd}}$, see Fig. 3. The minimum guaranteed channel depth $D_{\text{min}} = D_d + c_{\text{min}}$ is the sum of the draft of large ships $D_d$ and a minimum required clearance $c_{\text{min}}$ underneath the ship, which consists of under-keel clearance required for maneuverability, ship movements (squat, pitch, roll) and other uncertainties such as bathymetric measurement errors. The mean water depth before dredging is $H$. The sand wave profile in the model is defined by $z = z_b(x, t)$.

Table 1

| Description                  | Symbol | Typical value | Unit |
|-----------------------------|--------|---------------|------|
| M2 tidal velocity amplitude | $U_{M2}$ | 0.5           | m s$^{-1}$ |
| M2 tidal angular frequency  | $\omega_{M2}$ | $1.41 \times 10^{-4}$ | rad s$^{-1}$ |
| Wind speed                  | $U_{\text{wind}}$ | 10            | m s$^{-1}$ |
| Wind angle                  | $\theta_{\text{wind}}$ | 0             | deg |
| Wave height                 | $H_{\text{wind}}$ | 3             | m |
| Wave angle                  | $\theta_{\text{wave}}$ | 0            | deg |
| Wave period                 | $T$   | 7             | s |
| Vertical eddy viscosity     | $A_v$ | 0.04          | m$^2$ s$^{-1}$ |
| Slip parameter              | $S$   | 0.01          | m s$^{-1}$ |
| Bed porosity                | $\rho$ | 0.4           | -- |
| Gravitational acceleration  | $g$   | 9.81          | m$^2$ s$^{-1}$ |
| Water density               | $\rho_w$ | 1 020        | kg m$^{-3}$ |
| Air density                 | $\rho_a$ | 1.225         | kg m$^{-3}$ |
| Wave friction factor        | $f_w$ | 0.1           | -- |
| Mean water depth            | $H$   | 30            | m |
| Bed load coefficient        | $\alpha_b$ | $1.56 \times 10^{-5}$ | m$^3$ s$^{-1}$ kg$^{-\alpha}$ |
| Bed load exponent           | $\beta_b$ | 1.5           | -- |
| Slope correction parameter  | $\lambda$ | 1.5          | -- |
| Domain length               | $L$   | 350 or 4 000  | m |

* Default water depth, if not changed by a dredging intervention.
* For short and long domain, resp.

Fig. 4. Seabed evolution towards a model equilibrium sand wave. The top panels (a) and (b) show in black the seabed profiles just before a dredging intervention is applied. The coloured lines show the dredged profiles: solid (topping), dotted (swiping). The bottom panels (c) and (d) show the seabed evolution in space and time, for the single sand wave domain and the longer domain with a sand wave field, respectively.

Fig. 5. Profile of a sand wave in equilibrium, showing the two types of dredging interventions: (a) topping, and (b) swiping. Sand extraction in red, sand deposition in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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2.3. Initial profile: single sand wave vs sand wave field

Modeling dredging requires a sand wave profile, that is realistic from the perspective of the processes in the model. Following Campmans et al. (2018), we consider such profiles on two domain sizes.

**short domain** On a short domain (350 m) we let the model evolve to an equilibrium profile.

**long domain** On a long domain (4 km), starting from a randomly perturbed seabed, we let the model evolve to an irregular sand wave field in which the sand wave heights no longer show significant changes.

The above profiles (Fig. 4) serve as initial profiles when modeling dredging interventions, as further specified below. The parameters used for these simulations are shown in Table 1.

2.4. Modeling different dredging strategies

In this model study two different dredging strategies are considered, i.e. ‘topping’ and ‘swiping’ (Fig. 5). In both cases, the sand wave crest is partly removed to a design dredge depth $D_{dd}$. In the case of topping, the sand is taken out of the system (Fig. 5a). In the case of swiping, the sand is placed in the trough (Fig. 5b). These two dredging types are investigated for different values of the design dredge depth $D_{dd}$. The design dredge depths are chosen such that they correspond to prescribed dredge volumes $\Delta V$ for a given initial sand wave profile.

First, we investigate the response to a single topping or swiping event (RQ1 in Section 1). This is done on both the short and long domain, see Sections 3.1 and 3.3.

Subsequently, to study the temporal aspect of sand wave dredging (RQ2), we let the profile evolve until the minimum water depth in the model domain becomes smaller than the guaranteed depth $D_{min}$. As soon as this occurs, the profile is swiped instantaneously down to the design dredge depth $D_{dd}$. After this intervention, the profile will freely evolve again, until a next dredging intervention is required. Both the instantaneous and cumulative dredging volumes $\Delta V$ and $V$, respectively, as well as the dredging moments are analyzed. We do this for different values of the design dredge depth $D_{dd}$. Herein, we have chosen swiping (instead of topping), because this is a sand conserving dredging strategy that will maintain the mean water depth $H$ throughout the simulation, which facilitates analysis and interpretation. The temporal dredging strategy is studied on the short domain only, as it allows for simulations within reasonable computational time, starting from realistic equilibrium sand wave profiles.

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**Fig. 6.** The response of the sand wave crest and trough levels to two types of dredging interventions: (a) topping and (b) swiping. The line colors indicate the volume of the dredging interventions, blue $\Delta V = 50 \text{ m}^2$, red $\Delta V = 100 \text{ m}^2$, yellow $\Delta V = 150 \text{ m}^2$ and purple $\Delta V = 200 \text{ m}^2$ (black denotes the original, undredged, sand wave). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Fig. 7.** (a) The response of the sand wave crest and trough to recurring dredging interventions of the type swiping. The thin coloured lines are the design dredge depths $D_{dd}$. The thin black line is the guaranteed depth $D_{min}$. (b) The cumulative dredged volume $V$. Table 2 shows the timing and volumes corresponding to the shown results.
3. Results

3.1. Single dredging intervention in a short domain

Fig. 6 shows the crest and trough evolution after various dredging interventions of the equilibrium sand wave profile obtained in Section 2.4. For both intervention types the model simulations evolve towards an equilibrium profile. From run to run, the dredged material $\Delta V$ (volume per meter crest length) in the simulations is varied with increments of 50 m$^3$ up to 200 m$^3$ of sand.

Topping interventions instantaneously change the crest elevation. Sand is being extracted, resulting in an increase in mean water depth $H$. The sand wave crest regrows, to a value slightly below the pre-dredged crest elevation. The trough elevation decreases, as well, such that the resulting sand wave height increases with respect to its pre-dredged value.

Swiping interventions instantaneously change both the crest and the trough elevations. In this intervention, the amount of sand extracted from the crest is dumped in the trough leaving the mean water depth unaffected. For each of the dredged volumes the simulations return to the original equilibrium profile. However, larger interventions take more time to reach the equilibrium state.

For both intervention types, the results show that the larger the intervention volume is, the longer it takes for the system to re-establish a new equilibrium state. For the same dredged volume $\Delta V$, swiping is seen to be much more effective.

3.2. Recurring dredging interventions in a short domain

Fig. 7 shows the evolution of crest and trough elevations when dredging takes place as soon as the crest elevation violates the minimum guaranteed water depth. In these simulations, the values of the design dredge depth $D_{dd}$ are chosen such that they correspond to the dredge depths in the single dredging activity (Table 2, top row). For small design dredge depths the amount of dredged sand per intervention is relatively small. However, the time until the next intervention is shorter compared to that for larger design dredge depths. Notice that the time between subsequent dredging events is not constant; it increases until reaching an equilibrium return period, see Table 2.

The cumulative dredged volume $V$ is initially small for small design dredge depths. However, on the long term the dredged volume per unit time is what determines the most efficient strategy. For example: in our simulations, the swiping dredging strategy V50 needs to dredge $\Delta V = 10.6$ m$^3$ every $\Delta t = 2.6$ yr (Table 2), corresponding to $\Delta V/\Delta t = 4.0$ m$^3$/yr once it reaches dynamic equilibrium. The swiping strategies V100, V150 and V200 require 4.5 m$^2$/yr, 4.5 m$^2$/yr and 4.0 m$^2$/yr,
respectively. Note that the V150 and V200 strategies are possibly not yet in dynamic equilibrium. These results suggest that from a volume per time perspective there are two optimal design dredge depths: firstly, frequently dredging small volumes and secondly, flattening the sand wave as well as possible. Dredging small volumes lets the sand wave stay close to its equilibrium and hence grow back slowly because it is nearly saturated. Dredging very large amounts brings the sand wave back to its linear exponential growth, which is very slow for small amplitudes. Note that dredging small volumes is only possible when the crest heights of sand waves in equilibrium are close to the guaranteed depth.

3.3. Single dredging intervention in a long domain

So far, the response of sand waves to dredging has been investigated for a single sand wave on a periodic domain. This represents a field of identical sand waves that are all being dredged in exactly the same manner. Dredging activities typically take place locally, and in an irregular sand wave field. We start from a well developed sand wave field, formed on a model domain of 4 km through self organization from small random perturbations in the seabed. After 30 years of sand wave growth two different dredging scenarios are investigated. Firstly, a topping and secondly a swiping intervention of the largest sand wave in the model domain. The dredged volume of both interventions is 2000 m$^2$. Fig. 8 shows the development of a sand wave field starting from random perturbations in the seabed, as well as the response to the two types of interventions after 30 years. In both cases, directly after the intervention, clearly the dynamics of the dredged sand wave changes. This sand wave experiences a reduction in migration speed and, at least initially, it shows recovery. Not only the dynamics of the dredged sand wave changes, but also that of the surrounding sand waves. Differences in migration speed cause sand waves to merge together or drift apart. The swiped sand wave merges with the one to its left, while the dredged sand wave would have merged with the sand wave to its right in the undredged case, but this is prevented, or at least delayed, by both of the dredging intervention. The location, dredging type, dredging volume and moment and time all strongly affect the resulting sand wave response due to the strong non-linearity in the model.

4. Discussion

4.1. Qualitative interpretation of dredging strategies

Our model study showed qualitatively that dredging strategies require a long time to regenerate towards an equilibrium state in channel maintenance. Quantitatively, sand wave heights and sand wave recovery will probably for a long time rely on empirical models. However, qualitative insights provided by process-based models, give hints which terms could be included in new empirical models.

4.2. Shape effects

The results from Section 3.2 showed that the return period of dredging interventions depends on the shape of the sand wave after dredging. Simply the minimum water depth, a design dredge depth and a theoretical sand wave height cannot fully describe the return time for dredging. Empirical models such as Landau type of equations (e.g. Knaapen and Hulscher, 2002) would require different coefficients in between the consecutive dredging events to adequately describe the observed sand wave response. To show that the behavior of sand wave recovery is not merely a function of sand wave amplitude the results from Section 3.2 have been plotted as dA/dt versus A in Fig. 9. The lower grey curve shows that the sand wave amplitude evolution from a small perturbation towards an equilibrium sand wave can be described as a unique function dA/dt = f(A). Along this curve the shape of this

Fig. 8. The response to two dredging activities in a long-domain model run: panel (a) shows the autonomous evolution of a sand wave field from a randomly perturbed initial seabed (t = −30 yr). Panels (b) and (c) show the seabed evolution when at t = 0 yr the biggest sand wave in the field is being topped and swiped, respectively. Panel (d) shows the profiles at t = 0 yr with the extracted sand volume in red and, in case of swiping, the deposited volume in green. The swiped volume is placed in the deepest trough next to the sand wave crest. Panels (e) and (f) show the difference of the undredged and the dredged seabed elevation of topping and swiping, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
sinusoidal perturbation changes towards its equilibrium shape (Fig. 9d). However, this only concerns a single, rather arbitrary simulation. Alternatively, the black lines show simulations starting from sinusoidal shapes with different amplitude. The larger the amplitude of the initial sinusoidal shape, the further the black line moves away from the grey curve. This already indicates that sand wave dynamics cannot be captured as a unique function of amplitude only. Furthermore, the coloured lines show the four dredging strategies in amplitude perspective. The post-dredging evolution starts well above the grey curve, and then quickly move towards it. This again demonstrates that the shape of sand waves matters: general sand wave dynamics cannot be modeled as a function of amplitude alone.

This, however, does not render the Landau equation (1) useless. In fact, taking the coefficients $c_0 = 0.0575 \text{ s}^{-1}$ and $c_1 = 0.0116 \text{ m}^2 \text{ s}^{-1}$ turns out to adequately describe the amplitude evolution of the undisturbed sand wave (Fig. 10). Importantly, directly after dredging, the amplitude evolution strongly deviates from the Landau curve. To show this, we have plotted each individual recovery shifted in time, such that its next dredging event occurs at $t = 0$. It is seen that the amplitude initially recovers much faster than the Landau curve would suggest. After this initial recovery, the amplitude is found to follow the Landau curve again. As a result, the recovery times $\Delta t_{\text{new}}$ of our model results are shorter than those suggested by the Landau model. The recovery time $\Delta t_{\text{Lan}}$ according to the Landau model can be found analytically and is given by:

$$\Delta t_{\text{Lan}} = \int_{A_0}^{A_1} \frac{1}{c_0 A - c_1 A^2} dA = - \frac{\ln\left(\frac{c_0 A_0^2 - c_1 A_0^4}{c_0 A_1^2 - c_1 A_1^4}\right)}{2c_0}.$$  \hspace{1cm} (2)

Here $A_0$ is the sand wave amplitude instantly after dredging and $A_1$ the amplitude just before the next dredging event. The amplitudes $A_0$, $A_1$ and the recovery times $\Delta t_{\text{new}}$ and $\Delta t_{\text{Lan}}$ are given in Table 3.

### 4.3. Domain size and sediment conservation

Our model simulations are sediment conserving, except at the moment of non-conserving dredging interventions. The boundary conditions on either side of the model domain are spatially periodic, such that no sand can leave or enter the system. Removing sand from the system (as with topping, not with swiping) will therefore result in a permanent reduction in the mean seabed level. In the long domain
simulation sand is being imported to the dredging location from elsewhere in the domain. This enables us to investigate the interaction between a dredged sand wave and its non-dredged neighbours.

We investigated the effects of various dredging interventions on a single equilibrium sand wave on a horizontally periodic model domain. This periodic model domain allowed us to investigate sand wave evolution towards equilibrium states. However, the periodic model domain also restricts the adaptation of the sand wave wavelength, and does not allow to investigate the effect on the preferred wavelength. Simulations with a longer domain length show that initially sand waves have a preferred wavelength. However, as time progresses sand waves tend to increase in wavelength. Initially the speed at which the wavelength increases is relatively large, and gradually slows down, but does not stop until it meets the periodic domain length. This behavior seems to be consistent with the very small, yet positive, growth rates for very small wave numbers around wave number $k = 0$ in the linear regime obtained using linear stability analysis (Campmans et al., 2017). In a different context, Niemann et al. (2011) and Warmink et al. (2014) both developed morphodynamic models in unidirectional flows that show splitting behavior of dunes which may lead to a finite wavelength of bed forms.

5. Conclusions

Using a nonlinear process-based sand wave model, we have investigated the response of sand waves to two types of dredging activities with varying volumes. Results show that, the larger the intervention volume is, the longer it takes for sand waves to reach an equilibrium state. For the same volume of sand, the so-called ‘swiping’ technique is most effective in keeping a sand wave away from its equilibrium state the longest, as compared to the alternative ‘topping’ technique.

Topping sand waves initially reduces the crest height, and by removing sand from the system it also increases the mean water depth. By increasing the mean water depth, the equilibrium sand wave height increases, such that the crest elevation is hardly different compared to the previous equilibrium crest elevation. The sand waves reach their new equilibrium state more quickly with topping compared to the swiping technique.

The most important conclusion regarding temporal dredging frequency is that the time between subsequent dredging events is not constant. In our simulations, starting from a natural equilibrium, initially this interval is relatively short and it gradually increases towards an equilibrium.

Our results show that regrowth of sand waves after dredging is more than only a function of sand wave height before and after dredging, as it also includes sand wave shape and it significantly influences the neighbouring sand waves. Therefore, modeling sand wave recovery, which involves changes in the sand wave profile, requires a fully nonlinear process-based model rather than an empirical Landau type of predictor in terms of amplitude only. The added value of this process-based model particularly applies to the recovery directly after dredging and less to the subsequent recovery, for which the Landau equation seems adequate.

CRediT authorship contribution statement

**G.H.P. Campmans:** Methodology, Software, Formal analysis, Investigation, Writing - original draft, Visualization. **P.C. Roos:** Project administration, Funding acquisition, Supervision, Writing - review & editing. **N.R. Van der Sleen:** Resources, Writing - review & editing. **S.J. M.H. Hulscher:** Funding acquisition, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is part of the research programme SMARTSEA with project number 13275, which is (partly) financed by the Netherlands Organization for Scientific Research (NWO). The authors thank Ad Stolk from Rijkswaterstaat Zee en Delta for discussions on this work.

## Appendix A. Model formulation

The model formulation in this appendix follows from Campmans et al. (2018). It consists of hydrodynamic, sediment transport and bed evolution equations, and boundary conditions.

### Appendix A.1 Hydrodynamics

The hydrodynamics are described by the (2DV) shallow water equations consisting of a momentum and a continuity equation given by

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial z}{\partial x} + F_z - A \frac{\partial^2 u}{\partial x^2} = 0,
\]

(A.1)
\[
\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0. 
\]  

(A.2)

Here \( u \) and \( w \) are the velocity components in the x- and z-directions, \( \zeta \) is the surface elevation in response to topographic changes, \( F \) the spatially uniform pressure gradient that forces the tidal flow, \( g \) the gravitational acceleration and \( A_v \) is the constant vertical eddy viscosity. The boundary conditions at the water surface and at the seabed are given by

\[
w = 0, \quad A_v \frac{\partial u}{\partial z} = \frac{\tau_{\text{wind}}}{\rho} \quad \text{at} \quad z = 0, \tag{A.3}
\]

\[
w = u \frac{\partial z_b}{\partial x}, \quad \tau = A_v \frac{\partial u}{\partial z} = \dot{S}u, \quad \text{at} \quad z = z_b. \tag{A.6}
\]

Here \( \tau_{\text{wind}} \) is the wind shear stress at the water surface, \( z_b \) the vertical position of the bed, \( \tau \) the bed shear stress due to tidal and wind-driven flow and \( S \) the slip parameter. Horizontally the domain has periodic boundary conditions, matching flow conditions at \( x = 0 \) with those at \( x = L \). The M2 tidal flow is prescribed by a depth-averaged velocity amplitude \( U_{M2} \) and an angular frequency \( \sigma_{M2} \). The tidal forcing term \( F \) is chosen such that – in absence of wind forcing and over a flat bed – the depth-dependent flow meets the following integral

\[
\frac{1}{H} \int_{-H}^{0} u \, dz = U_{M2} \sin(\sigma_{M2} t). \tag{A.4}
\]

The wind shear stress \( \tau_{\text{wind}} \) is given by

\[
\tau_{\text{wind}} = \rho_a C_d |U_{\text{wind}}| U_{\text{wind}}, \tag{A.5}
\]

where \( \rho_a \) is the air density, \( U_{\text{wind}} \) the wind velocity in x-direction at 10 m above the water surface and \( C_d = (0.75 + 0.067|U_{\text{wind}}|)10^{-3} \) is a drag coefficient (Makin et al., 1995). The total bed shear stress \( \tau_{\text{cw}} \), due to both currents and waves, is modeled by

\[
\tau_{\text{cw}} = \tau + \tau_w. \tag{A.6}
\]

Here \( \tau_w \) is the shear stress due to waves and is modeled by

\[
\tau_w = \frac{1}{2} \rho w |u_w| u_w, \tag{A.7}
\]

where \( \rho \) is the water density and \( u_w \) is the near-bed wave-orbital velocity. The wave kinematics are modeled by linear wave theory (e.g. Mei, 1989). The near bed orbital velocity is given by

\[
u_w = \frac{\sigma_w H_w \cos(\sigma_w t)}{2 \sinh(-k_w z_b)}. \tag{A.8}
\]

Here \( \sigma_w \) is the angular wave frequency, \( H_w \) the local wave height and \( k_w \) is the local wave number. Local, because they depend on the local water depth \( -z_b \). The local wave number \( k_w \) follows from the dispersion relation

\[
\sigma^2_w = g k_w \tanh(k_w z_b). \tag{A.9}
\]

The local wave height \( H_w \) is given by the shoaling relation

\[
H_w = \sqrt{n \sigma_c H_0}. \tag{A.10}
\]

where \( n \) is given by

\[
n = \frac{1}{2} + \frac{-k_w z_b}{\sinh(-2k_w z_b)}. \tag{A.11}
\]

and the wave celerity \( c \), by \( c = \sigma_w / k_w \). The quantities with a zero subscript, \( n_0, c_0 \) and \( H_0 \), are the wave conditions following linear wave theory at the mean water depth \( H \). The wave height is prescribed at the mean water depth.

Appendix A.2Sediment transport

Sediment transport is modeled by a bed load formula that includes a bed slope correction term

\[
q_b = d_b \left( \frac{\tau_{\text{cw}}}{|\tau_{\text{cw}}|} - 2 \frac{d \dot{S}}{dx} \right). \tag{A.12}
\]
Here $\alpha_b$ is the bed load coefficient, $\beta_b$ the bed load exponent and $\lambda$ is a slope correction parameter.

**Appendix A.3 Bed evolution**

The seabed evolution is modeled by the Exner equation

\[
(1 - p) \frac{\partial \zeta_b}{\partial t} = -\frac{\partial \langle q_b \rangle}{\partial x},
\]

where $p$ is the bed porosity and $\langle q_b \rangle$ the wave and tide averaged bed load transport flux.

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