FORM ROUGHNESS INDUCED BY TIDAL SAND WAVES: A MODELLING STUDY

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INTRODUCTION

Tidal sand waves are rhythmic bedforms usually found in tide-dominated shelf seas (e.g., the Dutch Continental Shelf, Figure 1). They are characterized by wavelengths of 100 - 1000 m, heights of 1 - 10 m and migration rates of 1 - 10 m/yr (van Dijk & Kleinhans, 2005). It is recognized that tidal sand waves generate form roughness that affects the hydrodynamics on a larger spatial scale. However, in basin-scale hydrodynamic models (that do not resolve the local sand waves), bed roughness is treated as a calibration parameter, and not directly linked to the local sand wave characteristics (Zijl et al., 2018).

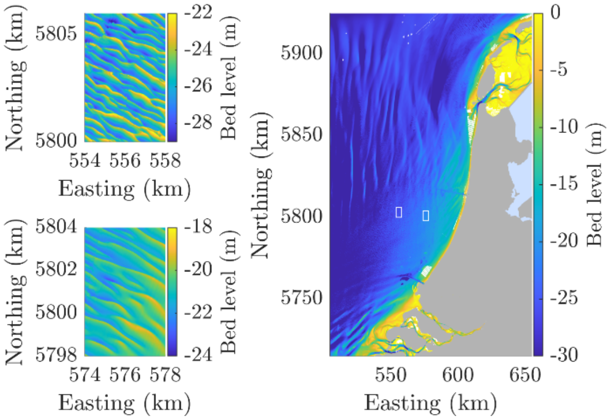

Figure 1 - Bathymetric chart of the Netherlands Continental Shelf, highlighting two examples of sand wave fields (white boxes). Data from Netherlands Hydrographic Service.

The total roughness that the flow experiences is usually expressed as the sum of grain roughness (skin friction) and form roughness (van Rijn, 2007). The latter is caused by bedforms. The existing form roughness parametrizations for river dunes and ripples predict values of the same order of magnitude as the grain roughness, highlighting its importance. Importantly, all existing studies focus on unidirectional and steady flow over a bedform, either river dunes (Lefebvre & Winter, 2016), or ripples (van Rijn, 2007). However, the steady and unidirectional flow settings used in these studies do not represent the oscillatory tidal flow experienced by tidal sand waves.

Here, we study the form roughness induced by sand waves in a tidal setting. To this end, we use two process-based hydrodynamic models. Firstly, a second order perturbation approach (based on the linear stability analysis of Hulscher, 1996) allows us to study the sand wave-averaged effects of sand waves on an oscillatory tidal flow. Secondly, Delft3D allows us to study the effects of sand waves on a propagating tidal wave. The setting used is an extension of that of van Gerwen (2018). Since we are interested in hydrodynamics over a fixed bed, we do not consider the morphodynamic evolution.

SECOND ORDER PERTURBATION APPROACH

The second order perturbation approach is based on the expansion of the system around a basic state (that with a flat bed),

$$\phi = \phi_0 + \epsilon\phi_1 + \epsilon^2\phi_2 + \mathrm{h.o.t.}\ , \qquad (1)$$

where ϕ represents any property of the system (e.g., flow velocity, sea surface elevation, bed profile) and ϵ is infinitely small. We consider this expansion up to second order and neglect higher order terms. Second order terms are needed since this is the lowest order at which the influence of the sand waves on the spatially uniform flow is felt. Equation (1) is applied to the 2DV shallow water equations. The bed roughness is introduced through the slip parameter s, used in the boundary condition at the bed,

$$\frac{\tau_{\mathrm{bed}}}{\rho} \equiv A_{\mathrm{v}} \frac{\partial u}{\partial z} = su \quad \text{at } z = -H + \epsilon h(x)\ . \qquad (2)$$

Here, τ_{bed} is the bed shear stress, and ρ is the density of water. The bed level is defined as the sum of the mean water depth H and the small-amplitude perturbations $\epsilon h(x)$. The eddy viscosity, A_{v}, is assumed constant and uniform, and u is the horizontal component of the flow. Note that the sea surface boundary conditions can be applied at the undisturbed water level instead because of the rigid lid approximation. The tidal forcing is considered to be uniform and oscillatory.

DELFT3D

The Delft3D model solves the 2DV shallow water equations in (x, σ)-coordinates. Turbulence is computed using the $k - \epsilon$ model. The bed roughness f is used to compute the bed shear stress τ_{bed},

$$\frac{\tau_{\mathrm{bed}}}{\rho} \equiv A_{\mathrm{v}} \frac{\partial u}{\partial z} = f|u|u \quad \text{at } z = -H(x)\ . \qquad (3)$$

Here, g is the gravitational acceleration. We impose a Riemann invariant at each side of the domain, which results in a propagating tidal wave. A Riemann invariant is a combination of flow velocity and sea surface elevation, and it ensures that no reflection of the tidal wave occurs at the boundaries.

QUANTIFICATION OF FORM ROUGHNESS

With both models, we perform simulations with different sand wave height ($\hat{h}$), and wavelength (λ). Default values for $\hat{h}$ and λ are 4 m and 350 m, respectively. Both models have a mean water depth of 30 m, and are forced with an M2 signal. The background slip parameter s_0 for the second order perturbation approach is 10^{-3}m/s, and the background friction coefficient f_0 in Delft3D is $2.3 \cdot 10^{-3}$.

Both models have a different representation of the tidal wave, thus a different quantification of the flow is needed to compute a form roughness.

Bed roughness is included in the second order perturbation approach with the slip parameter s used for the boundary condition at the seabed (Equation 2). The sand wave-averaged, depth-integrated flow signal over a sand wave field (with the background slip parameter s_0) is compared with that over a flat bed (with an increased 'effective' slip parameter $s_{\text{eff}} > s_0$). The additional value needed for the slip parameter such that both flow signals have the same amplitude or phase is then the form roughness, i.e. $s_f = s_{\text{eff}} - s_0$. Importantly, this leads to two form roughness values, amplitude-based and phase-based, which are not necessarily identical.

For the Delft3D simulations, we follow a similar approach but we do not take the sand wave-averaged signal because of the propagating nature of the tidal wave. Instead, we take depth-integrated flow amplitude and phase at a position down-wave of the sand wave field. We compare these values with those obtained with a simulation with a flat bed and an increased friction. As before, the added friction needed for both signals to have the same amplitude or phase is the form roughness: $f_f = f_{\text{eff}} - f_0$, again producing amplitude-based and phase-based results.

RESULTS

Results show an increase in form roughness for increasing sand wave height (Figures 2a, 3a) and a decrease in form roughness for increasing wavelength (Figures 2b, 3b). Additional Delft3D simulations with varying sand wave asymmetry show almost no differences in the form roughness obtained (not shown). Interestingly, the form roughness obtained when imposing equal flow amplitude differs from the one obtained when imposing equal flow phase. Yet, both criteria yield the same qualitative dependencies on sand wave characteristics.

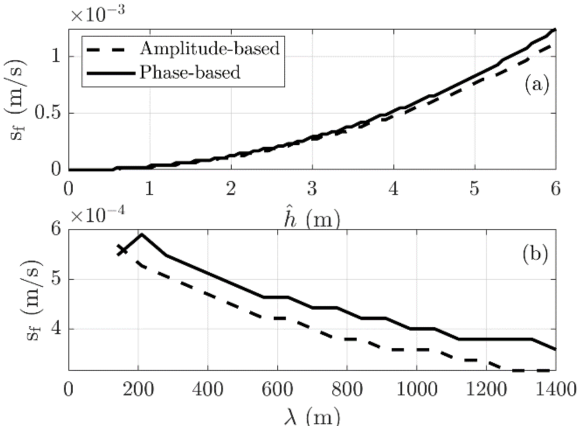

Figure 2 - Form roughness s_f as obtained by the second order perturbation approach depending on sand wave characteristics: (a) sand wave height, and (b) wavelength.

Furthermore, the obtained s_f-values with the second order perturbation approach (Figure 2) is one order of magnitude lower than the grain-induced s. In the finite-amplitude regime, the two roughness sources are of the same order of magnitude when imposing the phase criterion (solid line in Figure 3). Our results agree qualitatively with the dependencies on sand wave height and wavelength found for fluvial settings (Lefebvre & Winter, 2016).

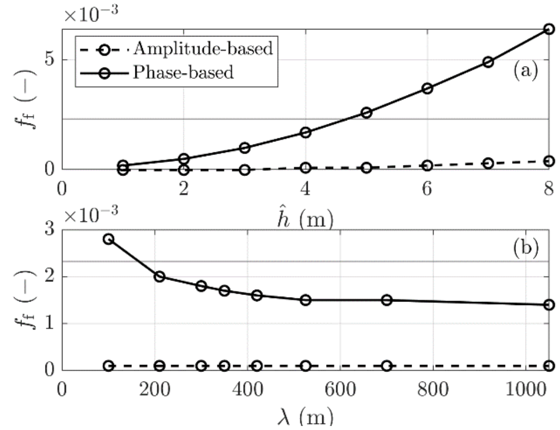

Figure 3 - Form roughness for a propagating tidal wave (Delft3D simulations) depending on sand wave characteristics: (a) sand wave height, and (b) wavelength. Horizontal thin line is the background value f_0.

CONCLUSIONS

Using two complementary process-based modelling approaches, we have successfully quantified the effects of sand wave height and wavelength on the form roughness experienced by an oscillatory flow and a propagating tidal wave. The differences between the amplitude-based and phase-based roughness values demonstrate the additional complexity when studying form roughness in a tidal rather than steady flow setting.

ACKNOWLEDGEMENTS

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