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Wave forcing over an intertidal mussel bed

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ABSTRACT

The Mosselwad project studies the stability and opportunities for restoration of mussel beds in the Wadden Sea. In this context we seek to predict mussel bed stability with respect to hydrodynamic forcing. To make accurate predictions with models, field experiments are needed to determine relevant processes and to establish representative estimates for model parameters. These parameter values were determined by a six week campaign on a relatively young mussel bed in the Wadden Sea. During this period wave height, period, propagation velocity, dissipation and flow velocities were measured. From these measurements values for the total rate of energy dissipation and the rate of wave energy dissipation were estimated. Results show a large increase in measured bed shear stress over the mussel bed compared with the uncovered parts of the intertidal flat. This is caused by the large roughness of the mussels. The turbulent kinetic energy was high above the covered parts of the bed. From the dissipation rate of TKE values for the corresponding bed shear stress and roughness height were estimated. These estimates were subsequently applied to calibrate a wave model which was used to determine the spatial distribution of the wave forcing. Model results show that the bed shear stress decreases over the mussel bed but increases behind the bed. Furthermore, a model study on the situation before the mussel bed settled shows that a minimum in wave forcing coincides with the seaward edge of the bed. This suggests that the bed is currently located in the optimal location with respect to wave forcing.

1. Introduction

Recently, an increase in shellfish restoration programmes has led to a growing interest into the relation between shellfish aggregations and hydrodynamical forcing. The Mosselwad project, which comprehends the present study, studies the stability and opportunities for restoration of mussel beds in the Wadden Sea. The goal of this study is to determine the hydrodynamical forcing on a mussel bed, and to quantify key parameters which can be used to predict survival chances of mussel beds. The chance for a mussel to erode is controlled by the byssus attachment strength to the bed and the forcing it is subjected to. It was demonstrated by Witman and Suchanek (1984) that the byssus attachment adapts itself to the wave forcing the mussel is subjected to. This adaptation results in a large spatial variation in attachment strength related to wave exposure (Witman and Suchanek, 1984). Later, it was demonstrated that this ability to adapt itself was limited by energy availability, related to food availability and temperature, resulting in seasonal variation in attachment strength (Carrington, 2002; Moeser et al., 2006; Price, 1980, 1982).

The effects of wave forcing on mussels were investigated by Denny (1987, 1995), in the late eighties and early nineties, who did extensive research on the relation between wave action and the forces exerted on shoreline organisms. He found that mussel erosion takes place by means of patch erosion instead of single mussel erosion (Denny, 1987). Patch erosion is controlled by three main forces acting on the bed (Denny, 1987), form drag, acceleration and lift. The relative importance of all these forces is controlled by water level, morphology and mussel density. Lift is found to be the most important mechanism under breaking waves (Denny, 1987; Gaylord, 1999), while form drag is considered to be the main mechanism under non-breaking conditions. Acceleration is only of importance near the bed edge.

Outside the viscous boundary layer above the mussel bed all three forces appear as shear stresses to both the flow and orbital velocities (Garratt, 1994). The dominant parameter for the wave forcing due to shear stresses under waves is the wave orbital velocity (Soulsby, 1997). The spatial variation of this parameter is controlled by the characteristics of the incoming wave field and its attenuation in the near-shore zone. The rate at which attenuation occurs is controlled by the water depth, and the amount of friction the wave is subjected to at the bed (Thornton and Guza, 1983). The spatial distribution of the wave forcing is thus controlled by the local morphology and the bed roughness.

The effects of currents on mussel bed stability were studied by Widdows et al. (2002) who showed that bed erosion by currents decreases the attachment strength of the mussel to the underlying substrate. Other studies showed the effects of currents over mussel beds in relation to sediment dynamics (van Leeuwen et al., 2010) and turbulent mixing (Van Duren et al., 2006). Currents havehowever not been directly related to erosion of the mussel aggregations. Brinkman et al.

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(2002) and Hammond and Griffiths (2004) have shown that there is an optimum in both wave orbital velocity and current velocity for which mussel bed abundance is the most common. The relation between the spatial distribution of mussel cover and hydrodynamical forcing on the scale of individual tidal flats has however never been investigated.

The main objective of our present study is to investigate and establish the main relation between hydrodynamic forcing due to waves and currents and representative parameters for current and wave friction. As a first step, field measurements were performed to assess the effects of the mussel beds on both the currents and waves to improve estimates for model parameters over mussel beds. Secondly, the relative importance of both wave and current forcing will be analysed. As a next step in our research approach the wave model SWAN (Booij et al., 1999) was applied to extrapolate our measured data to a much wider area of a tidal flat scale. We finalise by relating the results of this model study to the spatial distribution in mussel cover. Our paper is organised as follows. First, in Section 2 an overview is presented on methods to determine hydrodynamic forces acting on the bed. Next, our field experiment is described in Section 3. In Section 4 methods for data processing are presented and results of both the field research and model effort are shown. Subsequently, the results from the measurements as well as from the model study are integrated and discussed in Section 5. Finally, a summary of the results and the main conclusions are presented in Section 6.

2. Theory

Here, we present the theoretical framework to make estimations and predictions on the bed shear stresses applied by hydrodynamical forces on the bed. We present two methods by which the physical bed roughness k_b is estimated. First, we present the method for roughness height estimation based on turbulent dissipation. Secondly, we demonstrate another method that estimates roughness height from wave attenuation. Finally, it is shown how these estimates of the roughness height can be used to estimate the bed shear stress.

2.1. Roughness height estimation from turbulent dissipation

By means of high frequent velocity measurements both the wave averaged current velocity $\bar{u}(z)$ at height z and the dissipation rate of turbulent kinetic energy (TKE), called , can be determined. Subsequently, the current friction velocity (U_{*c}) can be estimated, assuming a balance between turbulence production and dissipation, by,

$$U_{*c} = \left(\epsilon\kappa z\right)^{1/3}, \tag{1}$$

in which $\kappa = 0.4$ is the von Kármán constant. In the case of a fully developed boundary layer flow the physical roughness height z_0 from the current friction velocity (U_{*c}) and the average velocity at height z are related via the law of the wall,

$$\bar{u}(z) = \frac{U_{*c}}{\kappa}\ln(z/z_0). \tag{2}$$

The roughness height z_0 is related to the physical roughness height k_b through $z_0 = 30k_b$. Waves cause oscillating flows near the bed. The boundary layer has no time to develop properly as velocities change fast in both magnitude and direction, resulting in a much thinner boundary layer, typically in the order of centimetres above the bed. For combined wave and currents the effects of the wave boundary layer on the mean velocity profile outside the wave boundary layer can be modelledas an increase in surface roughness (Grant and Madsen, 1979). Inside the wave boundary layer the mean current velocities are reduced by wave induced turbulence, this effect is modelled by Grant and Madsen (1979) and Madsen (1994) as an increased eddy viscosity in the wave boundary layer. Adopting their approach results in two equations describing the mean vertical current profile inside and outside the wave boundary layer;

$$\bar{u}(z) = \frac{U_{*c}^2}{\kappa U_{*_{cw}}}\ln(z/z_0) \quad z<\delta w, \tag{3}$$

$$\bar{u}(z) = \frac{U_{*_c}}{\kappa}\ln\left(z/z_{0_a}\right) \quad z>\delta w, \tag{4}$$

where, z_{0_a} is the apparent roughness, δw is the height of the wave boundary layer and $U_{*_{cw}}$ is the maximum shear velocity inside the wave boundary layer induced by both the current and wave orbital motion. From our measurements U_{*c} can be estimated using Eq. (1), the apparent roughness (z_{0_a}) can be estimated by solving Eq. (4) with our estimate for U_{*c}. In the first Eq. (3), however, two unknowns $U_{*_{cw}}$ and z_0 remain. In order to find estimates for both unknowns we apply the Grant and Madsen wave current interaction model (Madsen, 1994). This model predicts values for $U_{*_{cw}}$, U_{*_c} and z_{0_a} from measurements of the mean current velocity and the wave orbital velocity u_b at a reference depth, the representative wave period and the angle between the wave and current direction, additionally, the model requires an estimate for the roughness height z_0. The latter is the quantity of interest in order to determine z_0 we first estimate its value, which we subsequently use to calculate U_{*_c} and z_{0_a}. Next, we compare their respective values to our measurements and use that to update or estimate our value of z_0. This procedure is repeated until convergence for z_0 is achieved.

2.2. Roughness height estimation from wave attenuation

In order to estimate the roughness height from wave attenuation several pressure sensors were placed around the bed. By comparing the amount of wave energy that is transported past each pressure sensor per second, the wave energy flux (F), the loss in wave energy and the contribution of bed friction to this loss between two sensors was determined. Subsequently, the roughness height was estimated from the wave energy loss by bed friction. To achieve this we started by converting our pressure time series into time series of sea surface elevation. From these time series, under the assumption of linear wave theory the wave energy (E) and the velocity by which it propagates, the group velocity (C_g), can be determined. Furthermore,the current velocity (u) also influences the velocity at which the wave energy is transported, for each sensor we take the velocity of the most nearby sensor. This allows us to calculate the wave energy flux,

$$F_x = E\left(C_{g,x} + u_x\right), \tag{5}$$

here x stands for the component along the line between two sensors. By comparing the energy change between two sensor locations the average rate of change in wave energy flux can be determined,

$$\frac{\Delta F}{\Delta x} = \frac{F_{A,x} - F_{B,x}}{\Delta x}. \tag{6}$$

The wave energy flux is only changed by production p or dissipation e of wave energy, Δx is the distance between two sensor locations. In shallow water production of wave energy is much smaller than dissipation of wave energy, therefore, production is neglected. In shallow water there are two dissipative mechanisms, wave breaking and bed friction, the relative importance of each mechanism is mainly controlled by the bed slope.

$$\frac{\Delta F}{\Delta x} = e_b + e_f, \tag{7}$$

here e_b and e_f are the energy flux dissipation rates by wave breaking and bed friction respectively. Several models have been developed

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