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Mixing efficiency of sediment and momentum above rippled beds under oscillatory flows

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ABSTRACT

While the nature of the suspended load above steep, wave-induced, sand ripples is of practical importance, it also raises intriguing questions about the relative mixing efficiencies of sediment and momentum above the seabed. It has been widely accepted that the mixing efficiency of sediment is substantially greater than that of momentum. But, hitherto, this has not been explained clearly in terms of the underlying, detailed physical mechanisms which revolve around the generation and ejection of sediment-laden vortices at the ripple crest, and their subsequent advection by the flow. A two-dimensional discrete-vortex, particle-tracking research model, with the parameter settings corresponding to a well-documented laboratory experiment, is used here to represent these processes. Both the modelled and also experimental flow and concentration fields are described in detail, together with the horizontally (ripple-) averaged fields, and the cycle-mean, ripple-averaged fields. From these considerations, the ratio (β) of the sediment diffusivity to the eddy viscosity, or the inverse of the Schmidt number, is then determined. It is found that β is larger than unity, in fact between 1.3 and 3.1 for two different computational approaches (based on harmonics and exponential fitting) for the model and data. These values for β agree well with previous results reported in the literature. This research elucidates, from fundamental principles related to spatio-temporal correlations between concentration and velocity, the improved efficiency of sediment mixing compared with momentum mixing in the vortex layer above rippled beds and its key role in determining suspension profiles in such flows.

1. Introduction

The physical processes governing the transport of sediment above plane and rippled mobile beds in oscillatory flows induced by coastal surface waves are fundamentally different. While for plane beds a sheet flow layer mobilises the sediment as bedload close to the bed, above ripples vortices are created along the bed and ejected from the ripple crests at each flow reversal. These vortices are sediment laden and, thus, lift the bed sediment into suspension, increasing the amount of sediment transport (Davies and Thorne, 2008). Within the vortex layer, which extends to around one to two ripple heights above the bed, momentum transfer and the associated sediment dynamics are dominated by these coherent, periodic vortex structures (see, for example, Rodríguez-Abudo et al. (2013)). In practice, the detailed processes involved in the convection of vortices and of sediment by the flow within the vortex layer are such that the mixing of sediment is significantly more efficient than the mixing of momentum, as observed in field and laboratory experiments (Nielsen, 1992; Thorne et al., 2003, 2009; Van Rijn, 1993). Above this layer, the vortices break down and are replaced by more horizontally uniform turbulence, making the near-bed mixing of sediment and momentum similarly efficient (see Davies and Thorne (2008), and references therein). The greater effectiveness of sediment mixing than momentum mixing in the vortex layer is widely accepted amongst researchers, but has yet to be corroborated, and also explained, using detailed models; the effect is distinct from that which occurs above featureless beds under sheet-flow conditions (e.g. Dohmen-Janssen et al., 2001), since it relates directly to the movement of vortices.

Modelling of sediment transport above ripples under field-scale waves may be based on one-dimensional vertical (1DV), two-dimensional vertical (2DV) or three-dimensional (3D) formulations. For weaker waves, ripples are described as ‘orbital’ because their wavelength scales with the wave orbital diameter and they tend to be long-crested and 2D. In contrast, for stronger waves,

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ripples are described as ‘anorbital’ because they scale with the median grain diameter and tend to be 3D (Wiberg and Harris, 1994).

The processes affecting the evolution of the flow and the sediment concentration fields above rippled beds can only be captured in detail by using 2DV or 3D models. In 2DV models, the Eulerian convection–diffusion equation, introduced and developed in Appendix A, includes temporal changes with respect to time t, with sediment convection resulting from the instantaneous fluid velocity $\mathbf{u}=(u,w)$ accompanied by vertical sediment settling at a relative speed w_s, and diffusivity terms in the horizontal and vertical directions.

Provided that ripples are fully developed, and ripple morphodynamics are not being considered (Marieu et al., 2008), it is possible to assume that the sediment has little effect on the flow field. Thus, the hydrodynamic problem may be solved first over a fixed ripple shape, and the resulting 2DV velocity field can then be used in the advection–diffusion equation for the sediment concentration c. This assumption is valid for most of the water column, and hence it generally leads to good estimates of the sediment concentration (see, e.g. Hansen et al. (1994), Perrier (1996), Magar and Davies (2005) and Van der Werf et al. (2008)).

While 2DV models are, by their nature, research-oriented, more practical models tend to be based, at most, on 1DV methods that include parameterisations (Davies et al., 2002), the most important in the present context being the vortex shedding parameterisation. Although this vortex shedding and the associated (vertical) sediment transport are essentially convective processes, several authors have represented the effect as a diffusive process (Sleath, 1991; Van Rijn, 1993). As noted by Davies and Thorne (2005), a ‘convective eddy viscosity’ may be defined to represent the mixing of momentum in the vortex layer (ν_u), with an analogous convective sediment diffusivity (ν_c) defined to represent the mixing of the sediment, both of these quantities being strongly time-varying.

It has been further inferred by Nielsen (1992) and Sleath (1991), that due to the essentially height-invariant mixing length scale characterising the time-invariant components of both ν_u and ν_c in the vortex layer, the vertical profiles of both the velocity and the sediment concentration can reasonably be assumed to take simple functional forms. In particular, the sediment profile is expected to decay exponentially with height above the bed. The question that then arises is, whether due, on the one hand, to the nature of the vortex action, and, on the other, to the associated temporal signature of sediment entrainment from the bed, the ratio $\beta=\nu_c/\nu_u$ ($=1$/Schmidt number) is larger than unity within the vortex layer (rather than unity as is often assumed in more horizontally uniform turbulence). The main focus in this paper is on the time invariant components of the respective diffusivities and β is, therefore, defined on that basis, as in other works. According to the experimental evidence presented by Nielsen (1992), the value of β should be about 4, such that the transfer of sediment is as much as 4 times more efficient than that of momentum. Davies and Thorne (2005) demonstrated the importance of taking $\beta>1$ in 1DV models (extending this approach also to the time varying aspects of the process). If β is not assumed to be larger than unity then the vortex shedding process will not be parameterised well enough for the 1DV model to represent realistically the spatio-temporal correlations between high concentration and locally upward velocity (Amoudry et al., 2013). A 3D-mechanism, arising from the 3D-instability found by Hara and Mei (1990), may also be responsible for enhancing sediment in suspension above long-crested ripples (Watanabe et al., 2003). This 3D-mechanism can only be captured in 2DV or 3D models, hence the necessary parameterisation of this process in 1DV models, reflected by the value of β. Scandura et al. (2000) provided further insights into these mechanisms controlled by the action of two-dimensional vortex structures. As shown by these authors, these structures cause a pile-up of sediment particles at the ripple crests, which are then lifted up into the flow. They argued that this mechanism could create additional strong mixing, and increased dispersion.

The aim of this paper is to compute and analyse the sediment diffusivity in the vortex layer using both a 2DV research model and experimental data for a specific, well documented, test case. In particular, it is investigated whether mixing of sediment is more efficient than mixing of momentum, and if so by how much. The hydrodynamic model used is a discrete-vortex model that was developed by Malarkey and Davies (2002). This is coupled with a particle-tracking 2DV (or more explicitly, two-dimensional horizontal-vertical, or 2DHV) model for the sediment transport that was developed during the EU SANDPIT project (see Magar and Davies (2005)). The combined discrete-vortex, particle-tracking model has been validated against measurements obtained in the Aberdeen Oscillatory Flow Tunnel (AOFT), as described by Van der Werf et al. (2007). The interested reader is referred to Van der Werf et al. (2008) for wider aspects of the modelling approach, and detailed comparisons between the model and the experiments. For this work, the same experimental and modelling setups as in Van der Werf et al. (2008) are used, but here for considerations of the mixing efficiency of sediment compared with that of momentum above rippled beds, under oscillatory flows. For completeness, the experiment and the model are discussed briefly in Section 2. In Section 3, first the 2-dimensional experimental data and model results are presented, followed by the horizontally (ripple) averaged results, and finally by the cycle-mean, ripple-averaged results, from which the coefficient β is determined. The discussion and conclusion are presented in Sections 4 and 5, respectively.

2. Methods

2.1. Laboratory experiment and settings

The experiment considered here was conducted in the Aberdeen Oscillatory Flow Tunnel (AOFT). The AOFT has an overall length of 16 m and a glass-sided, 10 m long, 0.75 m high and 0.3 m wide rectangular test section. The flow was measured using particle image velocimetry (PIV) and the sediment concentrations using an Acoustic Backscatter System (ABS), as well as suction sampling. All of the measurements were carried out along the centre-line of the AOFT. The AOFT has a rigid upper lid, constraining the flow to be purely horizontal. Hence, in common with all wave tunnel experiments, there were no vertical wave velocity effects.

The test case under consideration is experiment Mr5b63, discussed in detail by Van der Werf et al. (2007). The sediment used for that experiment was a well-sorted medium sand, with median grain diameter $D_{50}=0.44$ mm. The free-stream velocity was based on a wave-tunnel equivalent to near-bed flow beneath Stokes second-order waves, of the form

$$u_\infty = U_1\cos(\sigma t-\gamma)+U_2\cos 2(\sigma t-\gamma), \tag{1}$$

where $U_1=0.54$ m/s and $U_2=0.09$ m/s are the first and second harmonics of the velocity amplitude, respectively, $T=5$ s is the wave period, $\gamma=80.9°$ is the phase such that $u_\infty(0)=0$, σ is the angular frequency ($=2\pi/T$) and t is time (U_1, U_2 and γ are based on fitting to the uppermost PIV measurement, but there may be other harmonics present in the data). For this skewed (velocity skewed) wave, positive velocities are in the implied onshore direction and negative in the offshore direction.